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[*Continued on page (III) of Cover.*

# HYDRO-ELECTRIC DEVELOPMENT IN GREAT BRITAIN, WITH SPECIAL REFERENCE TO THE WORKS OF THE GRAMPIAN ELECTRICITY SUPPLY CO.

By A. S. VALENTINE, Associate Member, and E. M. BERGSTROM.

[*Paper first received 8th November*, 1933, *and in final form 27th April*, 1934; *read before* THE INSTITUTION *8th November, before the* SCOTTISH CENTRE *13th November, before the* SOUTH MIDLAND CENTRE *19th November, before the* NORTH-EASTERN CENTRE *26th November, before the* MERSEY AND NORTH WALES (LIVERPOOL) CENTRE *3rd December, and before the* NORTH-WESTERN CENTRE *18th December* 1934; *also before the* SHEFFIELD SUB-CENTRE *16th January, before the* WEST WALES (SWANSEA) SUB-CENTRE *31st January, and before the* NORTH MIDLAND CENTRE *5th February*, 1935.]

## SUMMARY.

The paper deals with the general considerations relating to hydro-electric development in Great Britain, and describes the conditions under which such developments are practicable, and their limitations.

The various hydro-electric installations which have been constructed are referred to in general, and reference in detail is made to that of the Grampian Electricity Supply Co., covering the civil, mechanical, and electrical engineering works. A general description is also given of the principal features of the main distribution system, over which the bulk of the power generated is transmitted.

---

## INTRODUCTION.

Whilst water power in this country as an agency in the progressive development of the electrical power industry has, for reasons not far to seek, taken a less prominent place than that accorded to other sources of energy, it is nevertheless, in view of recent activities, interesting and—in certain respects—instructive to examine the present position of hydro-electric power in Great Britain by making a brief survey of the fundamental conditions which have governed the progress achieved so far in this field of development. It is admitted that the extent of such development has by necessity been limited as compared with countries more favourably endowed by nature for such opportunities, and where often water power constitutes the only national asset as regards production of power; but from the technical aspect the more recent developments in this country have many interesting features which merit attention and in general reflect the great strides made in Great Britain in a relatively short period, not only in the lay-out and construction of hydro-electric installations but also in the design and manufacture of all essential plant and equipment.

Water power as an aid to industry has, as is well known, been used in this country since the earliest times, and various industries, more particularly woollen manufacture and flour milling, were established along the principal waterways obtaining their motive power from overshot or undershot water wheels. Interesting relics of this past age are still to be found in many parts of the country.

With the arrival of the steam age, industries gravitated towards the coal-bearing areas, and the steam engine became the principal prime mover, although with the introduction of the earlier types of water turbines certain progress in water-power development can be recorded. Such development was, however, on a very modest scale, and at the beginning of the present century the census of power production showed that less than 2 per cent of the power requirements of this country was produced from water power. These water-power plants represented a large number of small installations operating through mechanical drives, and it was only with the advent of electricity that the application of water power on an extended scale could be envisaged. As a result of the unprecedented progress during the last few decades in respect of the generation and transmission of electrical energy, the employment of water power for both industrial and domestic purposes has made a rapid advance in those countries where opportunities exist for such developments within an economic radius of transmission. Also in this country, particularly since the War, attention has been focused on the special considerations attached to the problem of bringing our water-power resources within the scope of our industrial organization, in which the production of power occupies such a prominent position.

It is recognized that with a cheap and adequate supply of coal, on which the industries of this country are primarily dependent, water-power developments present an entirely different problem from that of other countries with abundant water-power resources. By reason of this fact that in Great Britain water power can only be regarded as a contributory element, supplemental and subordinated to the main power supply derived from coal, the technical and economic factors enter far more prominently into the problem of its utilization than in countries where the economic policy is dictated by far less onerous conditions and where the natural advantages facilitate the solution of the many difficult technical questions inevitably connected with water-power developments.

Moreover, account must be taken of the new set of conditions created by the recent co-ordination of supply of electric power on a national basis, which will to some extent exercise its influence, both economic and technical in character, upon the rational utilization of our water-power resources.

It is in the light of these considerations that the present state of development of hydro-electric power in Great Britain must be viewed. While the developments so far completed or under construction are not unimportant, there still remains considerable scope for development in certain districts, for the application of hydro-electric energy either as isolated plants serving direct a given industry or as a unit in an interconnected system for general distribution purposes.

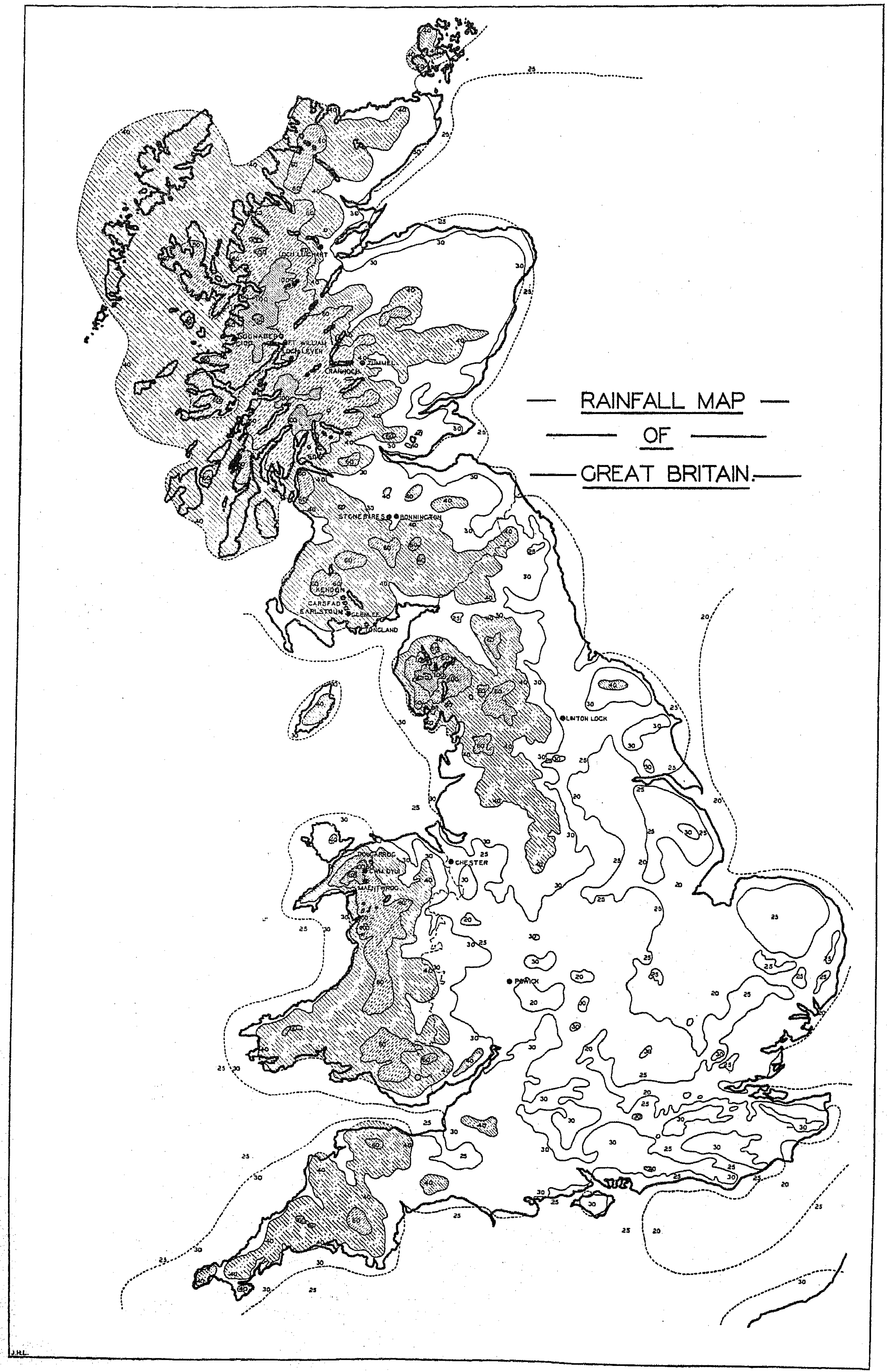
RAINFALL MAP
OF
GREAT BRITAIN.
LOCH LUICHART
LOCHABER
FT. WILLIAM
LOCH LEVEN
TUMMEL
RANNOCH
STONEBYRES
BONNINGTON
KENDOON
CARSFAD
EARLSTOUN
GLENLEE
TONGLAND
LINTON LOCK
DOLGARROG
CWM DYLI
MAENTWROG
CHESTER
POWICK
J.H.L.

Fig. 1.

A glance at a physical map of Great Britain (Fig. 1) will immediately indicate that the topographical features favourable to water-power development on a large scale are absent except in the Highlands of Scotland and certain areas in North Wales. The essential characteristics of large catchment areas, high average rainfall, steep gradients, and favourable sites for impounding reservoirs, are conditions not applicable to Great Britain as a whole. According to the report of the Water Power Resources Committee constituted by the Government in 1918, only 20 000 kW, or 8 per cent, of the output available at the potential water-power sites (considered capable of development at an economic rate and specially investigated under the auspices of the Committee), was located in England, the balance being divided between Scotland and Wales according to Table 1.

TABLE 1.

| | Area | Estimated output (continuous basis) | Percentage of total |
|---|---|---|---|
| | square miles | kW | |
| England .. .. | 50 053 | 20 000 | 8·0 |
| Scotland .. .. | 27 413 | 195 000 | 77·5 |
| Wales .. .. | 7 376 | 36 000 | 14·5 |
| | | 251 000 | 100·0 |

### ENGLAND.

The limited resources of England in respect of water power are easily appreciated in view of the low average elevation above sea-level, and the consequent flat gradients of the rivers, which must form the principal source for water-power development. Developments of any size cannot, therefore, be looked for, but notable examples of what can be achieved to a limited extent are provided by the installations at Chester and Worcester, and the more recent development at Linton Lock, York. In each of these instances an old mill site with existing weirs was utilized, and the installations were constructed for the purpose of supplementing the municipal electricity supply to the cities named. The available fall does not exceed 11 ft. in any of these installations, and the total electrical energy generated aggregates not more than an average of 5·25 million kWh per annum. This figure indicates the comparatively limited scope for installations of this type. There are numerous other examples of the conversion of obsolete water-power installations, and in these cases, with the increases in efficiency and specific speed obtained with the improved design of low-head turbines of the propeller type, and the automatic distant control of subsidiary hydro-electric stations, the purely technical problems have been solved satisfactorily. The result is a distinct advance on the earlier installations of this type. Viewed, however, as an adjunct to a general programme of electrification, it is doubtful whether any such installations could be economically justified except in isolated cases of localized rural electrification, situated at a distance from an area of existing supply.

### WALES.

Turning to Wales, we find the natural conditions more favourable to the possibilities of water-power developments, particularly in the northern area. Here the average annual rainfall is high, reaching the highest recorded in Great Britain (195in.) in the Snowdon district, and the favourable topographical features are indicated by mountain ranges of comparatively high altitudes with steep slopes amenable to a large percentage of "run-off." While these characteristics are favourable, the limited extent of the available catchment areas and the absence of adequate storage impose conditions incompatible with extensive power developments measured by the standard of modern requirements.

The earliest high-head installation in Great Britain was constructed in 1906 at Cwm Dyli, Beddgelert, utilizing the Llyn Llydaw watershed of the Snowdon range. It was authorized under the North Wales Power Act, 1904. Originally this undertaking was constructed for the purpose of supplying power to the principal slate quarries in the immediate district, but it has since been incorporated in the scheme for general supply in the North Wales area, to which reference will later be made.

The next development in this area was the original installation of the Aluminium Corporation, constructed in 1909 at Dolgarrog, utilizing surplus water from the catchment area of Llyn Cowlyd under agreement with Conway and Colwyn Bay Joint Water Board, who had possessed prior rights in this watershed since 1892. This installation was reconstructed in 1925 by incorporating the watershed of Lake Eigiau and other adjacent areas, and in this way the total watershed utilized was increased to about 17·5 square miles.

Under the provisions contained in the Electricity Act, 1919, application for an extended area was made by the North Wales Power Co., which controlled the above undertakings, and in 1923 the North Wales and South Cheshire Joint Electricity Authority was constituted, covering an area of supply of 4 080 square miles.

To meet the growing demand in this district a scheme was put forward for the construction of an additional hydro-electric plant at Maentwrog, and this was finally completed in 1928. This installation is situated in the county of Merioneth, and utilizes a total catchment area of 23 square miles under a head of 650 ft.

All the above hydro-electric stations (see Table 2) are interconnected and supply power in bulk to the authorized distributors in the area, as defined in the Order (1923) establishing the North Wales and South Cheshire Joint Electricity Authority. Subsequently this area has been included in the North-West England and North Wales Electricity Scheme, 1928, as authorized according to the Electricity (Supply) Act, 1926. Although the hydro-electric stations in the North Wales area are not "selected stations" under the provisions of the Act of 1926, special arrangements have been made by which they will be utilized in the generating programme of the area. For this purpose interconnection has been established at the Crewe transformer station between the grid and the North Wales system through a 66 000-volt double-circuit line from Maentwrog.

The total energy available from the hydro-electric plants in operation in North Wales is about 95 million units per annum.

This total can probably be increased to approximately 140 million units per annum by increasing the available water supply, particularly at Maentwrog. Apart from such extensions as have been indicated, no further comparatively large developments can be anticipated in Wales owing to the limited extent of available catchment areas.

In this connection it is also to be borne in mind that certain important watersheds in this area are already utilized by local authorities for water-supply purposes, and that, with the growing demand, further catchment areas must be reserved for meeting these requirements. There is, however, no reason for a conflict of interests as between the respective claims for use of the available water supply, because after the prior rights to water of the local authorities have been satisfied, surplus water can be made available for power purposes in cases where the general lay-out of the water scheme favours such development. Co-operation of this sort is beneficial to all the interests involved, and a precedent has already been provided by the joint utilization by local authorities and private enterprise of the water resources of Lake Cowlyd, to which reference has already been made.

TABLE 2.

| | Cwm Dyli | Dolgarrog | | Maentwrog |
|---|---|---|---|---|
| | | First installation | Second installation | |
| Catchment area, square miles .. .. | 1·6 | — | 17·5 | 22·5 |
| Average rainfall, inches per annum .. | 155 | — | 85 | 82 |
| Reservoir capacity, million cub. ft. .. | 123 | — | 417 | 1 150 |
| Average net head, ft. .. .. .. | 1 115 | 1 006 | 850 | 617 |
| Maximum load, kW .. .. .. | 4 500 | 5 200 | 10 000 | 15 000 |
| Plant installed, kW .. .. .. | 5 500 (a.c.) | 1 200 (a.c.),<br>4 000 (d.c.) | 10 000 (a.c.) | 24 000 (a.c.) |
| Output per annum, million kWh .. | 8–10 | — | 40–50 | 30–40 |

In connection with the water-power resources of Wales, investigations were made in 1918 of the possibilities existing in the upper reaches of the River Dee. In all, 16 low-head installations were projected, estimated to produce 60 million units per annum, with an output varying from 2 000 to 10 600 kW. Further investigations of this project from the point of view of capital cost would have to be undertaken, but with the extension of supply of electricity contemplated under the North-West England and North Wales Electricity Scheme it is to be regarded as doubtful whether the utilization of the low falls on the River Dee could be economically incorporated in this supply.

## SCOTLAND.

As has already been indicated, over 80 per cent of the available water-power resources in Great Britain are situated in the Highlands of Scotland. The topographical features are favourable, the country being mountainous and consisting mainly of impermeable strata with steep slopes and comparatively high average rainfall. This area is also characterized by its number of lochs, situated at a considerable elevation, which can be utilized as impounding reservoirs at low cost. Owing to the geographical position of this area in relation to the industrial centres farther south, its water power was up to a recent date regarded as capable of economic development only in connection with specialized industries such as electrochemical or electrometallurgical works.

The earliest hydro-electric industrial plant was constructed in 1896 at Foyers, on the Caledonian Canal. Its installed capacity of 5 000 kW was utilized in the reduction works established by the British Aluminium Co. for the production of aluminium, which process can only be economically adopted where cheap electric power is available.

In 1907 the same company extended its activities to Kinlochleven on the West Coast, where the most important hydro-electric plant at that time in Great Britain was authorized under the Loch Leven Water Power Acts of 1901 and 1904. This installation utilizes a catchment area of 55 square miles of the Blackwater river, and an impounding reservoir with a capacity of 3 200 million cub. ft. has been obtained by the construction of a concrete dam of gravity section across the same river. The annual rainfall amounts to 70–75 in., corresponding to an available water supply of 370 cub. ft. per sec.

From the intake at the dam the water is conducted through an open aqueduct constructed of concrete, with a total length of 3½ miles, to the forebay, from which point six lapwelded steel pipe-lines descend for a distance of 1¼ miles to the power house, where an effective head of 900 ft. is obtained. The power house is equipped with Pelton-wheel driven generators with a total output of 23 000 kW, which is all employed in aluminium production.

In view of the increased consumption of aluminium, particularly immediately after the War, further extensions of the British Aluminium Co.'s activities became necessary. For this purpose it was in the first instance decided to concentrate the production of aluminium at Kinlochleven and increase the power supply by diverting the adjacent catchment areas of Loch Treig and Loch Laggan by means of tunnels to a power house situated at Kinlochleven. Owing to parliamentary opposition, however, this scheme was ultimately abandoned, and a revised scheme for the construction of a power plant at Fort William was authorized under the Lochaber Water Power Act, 1921.

Work on the Lochaber water-power scheme was started in 1925, and the first section—completed in 1929—has an installed capacity of 50 000 h.p. When completed, the plant will have a total installed capacity of 120 000 h.p., and will constitute the largest hydro-electric station in Great Britain. The total catchment area of the full development is 303 square miles, situated in the south-west of Inverness-shire, extending from Loch Linnhe to the upper reaches of the Spey, and including Loch Laggan and Loch Treig, which form natural reservoirs. The rainfall over this area varies from 161 in. to 41 in. per annum. The flood waters of the upper reaches of the Spey are to be diverted by means of a dam and diversion-conduit into the River Pattack, which flows into Loch Laggan. A gravity dam is at present being built across the River Spean 4½ miles below Loch Laggan, and this will have the effect of increasing the length of the loch by means of a dredged channel. An earth fill dam which will have the effect of raising the loch by 35 ft., is being constructed across the River Treig. These two lochs are to be connected by a 15-ft. diameter tunnel, 2¾ miles long, which is now almost completed. The storage supplied by the two lochs is 9 318 million cub. ft. From Loch Treig a tunnel 15 ft. diameter and 15 miles long leads to a pipe-line 3 200 ft. long, the tunnel collecting water along its route from the slopes of the Ben Nevis range by means of intake shafts. The power house is situated about 3 000 ft. from the River Lochy, into which the tail-race discharges. As stated before, construction from Loch Treig to the power house was completed in 1929, since when this first stage of the scheme has been in operation. Provision was made for extending the pipe-line and power house up to the capacity of the full development. The present capacity of the power house, the turbines of which are of the Pelton type, consists of five units of 10 000 h.p. each, as well as auxiliary units. The present pipe-line consists of two pipes of 5 ft. 6 in. mean diameter. The maximum gross head available is 800 ft.

TABLE 3.

| | Kendoon | Carsfad | Earlstoun | Glenlee | Tongland |
|---|---|---|---|---|---|
| Catchment area, square miles .. .. | 152 | 171 | 193 | 49 | 396 |
| Average rainfall, in. .. .. .. .. | 56–66 | 55–66 | 53–66 | 57–70 | 43–70 |
| Estimated average run-off, in. .. .. | 44–56 | 43–56 | 41–56 | 45–60 | 29–59 |
| Top water level of reservoir, ft. (Ordnance datum) | 510 | 338 | 245 | 580 | 120 |
| Mean water level of reservoir, ft. (Ordnance datum) | 505 | 337 | 244 | 566 | 116 |
| Lowest water level of reservoir, ft. (Ordnance datum) | 502 | 336 | 243 | 540 | 110 |
| Average tail water level, ft. (Ordnance datum) | 338 | 267 | 175 | 168 | 9 |
| Gross fall, ft. .. .. .. .. .. .. | 167 | 71 | 70 | 412 | 111 |
| Approx. average net fall, ft. .. .. .. | 150 | 64 | 65 | 365 | 102 |
| Plant capacity, kW .. .. .. .. | 2 × 10 500 | 2 × 6 000 | 2 × 6 000 | 2 × 12 000,<br>1 × 500 | 3 × 11 000,<br>1 × 250 |
| Maximum load, kW .. .. .. .. | 21 000 | 12 000 | 12 000 | 24 000 | 33 000 |
| Maximum flow for power, cusecs. .. .. | 1 900 | 2 400 | 2 400 | 780 | 4 800 |
| Millions of units per annum .. .. .. | 36 | 18 | 20 | 40 | 68 |

These installations of the British Aluminium Co. provide an interesting example of an industry which could only be economically established in this country by reason of the availability of water power to a sufficient extent and at a low cost.

As has already been mentioned, the fact that the principal water-power sites in Scotland are at some considerable distance from the industrial and populous districts in the Lowlands and that there is no local demand in the immediate neighbourhood of the proposed developments, has until quite recently been responsible for the comparatively slow development of water-power utilization for general domestic or industrial purposes. The Lowlands of Scotland offer, however, to a limited extent, opportunities for hydro-electric enterprise. The Falls of Clyde have since 1926 been harnessed for power purposes as a supplementary supply for general distribution to the Clyde Valley Electrical Co., the authorized undertakers in this area.

The average rainfall in the upper reaches of the Clyde is 43 in. per annum, and a total catchment area of 385 square miles is utilized in two power stations constructed at Bonnington and Stonebyres respectively, about 3 miles apart. The lay-outs of the two stations are similar; the natural fall of the river being utilized by diversion of the flow through tunnels, 2 300 ft. long and 10 ft. in diameter at Bonnington and 1 550 ft. long and 11 ft. diameter at Stonebyres, the resulting effective heads being 174 ft. and 91 ft. respectively. In both cases single reaction turbines in vertical settings are employed. The installed capacity at Bonnington is 9 840 kW, and that at Stonebyres is 5 680 kW; thus the aggregate output is 15 520 kW.

A further development now under construction is the utilization of the River Dee in the county of Kirkcudbright, together with Loch Doon, authorized under the Galloway Water Power Act, 1929. The complete scheme involves the construction of five separate power stations with a total output of 102 000 kW, of which two, namely Glenlee (24 000 kW) and Tongland (33 000 kW) are now under construction. The date for the completion of the final scheme is estimated to be not later than the 1st August, 1936. These hydro-electric stations have been scheduled as " selected stations " under the South Scotland Electricity Scheme, 1931. The combined available output of hydro-electric power is estimated at 182 million units per annum, which has all been purchased by the Central Electricity Board under the provisions of the Electricity Act, 1926.

The hydraulic and technical details of this scheme, submitted by the promoters during the proceedings when the Bill was before the Select Committee of the House of Commons, are shown in Table 3. Numerous modifications in arrangement and detail have, however, been introduced since, during the progress of the development of the scheme.

In connection with the developments in the Lowlands of Scotland, a passing reference must be made to the Walkerburn hydro-electric scheme, Peebles-shire, completed in 1918. While the output available only amounts to 160 kW, obtained from two low-head turbines operating under a head of 11 ft., the interesting feature is that it is the only installation in this country utilizing mechanical storage of power. The power is employed for operating a mill during approximately 50 hours per week, and, as the continuous available flow (in the absence of natural storage facilities) is not sufficient for all requirements, mechanical storage of the available energy is resorted to. During the period of the day when the mill is closed down, the available power is used in pumping water into a storage reservoir of 560 000 cub. ft. capacity, constructed at an elevation of about 1 050 ft. above the power house. This storage is used in augmenting the power during the hours the mill is in operation, through the medium of a Pelton-wheel-driven generator having an output of 155 kW.

## The Present Situation in Great Britain.

In judging the results so far achieved, which are set out in Table 4, the position of water power in relation to other competitive systems of generation, in which coal—as far as this country is concerned—is the predominating factor, must be borne in mind. The economic standard by which the competitive possibilities of any water-power development can be judged is therefore definitely fixed, and it must be demonstrated that hydro-electric power in any given instance can produce power at any rate as cheaply as an alternative supply from coal on the same site.

If cost of transmission is left out of consideration in the first instance, it can be accepted as a general condition that the economic limit of capital cost of a hydro-electric installation is the amount represented by the sum of the capital cost of a thermal station of equivalent output and the capitalized value of the annual cost of fuel.

A more exact formula, giving effect to the differences in depreciation, cost of operation, transmission, and other comparable items of annual charges, can of course easily be evolved in any particular instance, but for the purpose of demonstrating the relative cost of the two competing systems the foregoing statement is sufficiently accurate.

Where the cost of coal is relatively low, as in this country, the economic margin of capital cost of water-power developments over and above the cost of steam installations is correspondingly reduced as compared with countries with high cost of fuel, and consequently the field for developments is much more restricted.

The importance of load factor is also easily appreciated. With continuous operation at a high load factor the economic margin in favour of hydro-electric power is increased, and it diminishes with a decreasing load factor to a point where the margin would be in favour of the steam plant.

For the supply of power to certain industries, other economic factors, such as transport of raw materials to any particular location and availability of skilled labour, enter into the problem; but for industries operating at a high load factor, and where the cost of electric power constitutes a large percentage of the cost of the final product, such as in most electrochemical or electro-metallurgical processes, the Highlands of Scotland offer scope for still further developments, the success of which has been manifestly demonstrated by the activities of the British Aluminium Co.

Again, the economic feasibility of utilizing a given catchment area is often determined by the combination of the physical characteristics in a manner which will produce the most favourable economic results. This can be achieved by considering the available hydraulic resources in a watershed on a comprehensive plan, whereby any existing impounding reservoir may be utilized to compensate the seasonal fluctuations in quantity of water in two or more stations situated in the same or an adjacent catchment area, and electrically interconnected. An example of such comprehensive treatment of a catchment area is afforded by the Rannoch and Tummel installations of the Grampian Electricity Supply Co., which will be described later in this paper.

The interconnection of steam and hydro-electric power plants will also promote the best economic results in certain cases by utilizing to the greatest advantage the available water flow, particularly if possibilities for storage are absent or deficient.

With the construction of the grid and the co-ordination of electricity supply on a regional basis, opportunities are afforded for a wider application of hydro-electric stations supplementing the supply from large steam generating stations. The Galloway power scheme, now under construction, is a notable illustration of this. It is contemplated that the hydro-electric stations as at present~~ly~~ constructed will supply peak-load power to the larger system with which they will be interconnected. This is a striking example of the benefits that can be derived from hydro-electric schemes when they are regarded as a unit in a larger development of power policy and are constructed according to an economic programme, taking advantage of the diversity of load and other conditions of supply favourable to a rational combination of the existing sources of power development.

This survey would not be complete without a reference to tidal power in Great Britain. The tidal conditions, from the point of view of power production, are most favourable on the west coast of England and Wales. Plans for a tidal-power station on the estuary of the River Severn have recently been the subject of a special investigation by a commission appointed by the Government.

The technical difficulties that have existed in obtaining efficient results from water turbines operating under the onerous conditions of widely fluctuating head of water have now been satisfactorily disposed of with the introduction of Kaplan or other types of propeller turbines. The technical problems as regards the purely mechanical or electrical equipment are therefore capable of satisfactory solution, although certain aspects of the construction of the necessary embankments and other structures, together with the questions relating to silting and navigation, must be specially investigated at each proposed site. The utilization of tidal power resolves itself, therefore, into an economic question in relation to other available or potential power supplies in the area. The cost of tidal-power developments is naturally closely linked with the topographical difficulties which have to be surmounted. As a general rule, the cost of the civil engineering works is considerable on account of the length of, and difficulty in finding suitable foundations for, the necessary embankments and "cut off" dams. For this reason such developments can only be considered at certain selected sites, as on the Severn, where the topographical features and other conditions in respect of the foundations, the tidal flow, and the geographical position in general, favour the production of a large block of electrical energy at the lowest possible cost per unit. The large amount of capital required for projects of this sort (for the Severn scheme the estimated capital expenditure exceeded £38 000 000) makes it unlikely that private enterprise alone could undertake the promotion of such schemes, which must rely on Government initiative or on a combination of interests represented by the Government, local authorities, and private enterprise.

TABLE 4.

*Principal Hydro-Electric Stations in Great Britain.**

| | Maximum net head | Capacity installed | Year completed | Owners |
|---|---|---|---|---|
| | ft. | kW | | |
| *England* | | | | |
| Chester .. .. .. .. | 9·0 | 635 | 1911 | Municipality |
| Worcester .. .. .. .. | 10·0 | 320 | 1912 | Municipality |
| York .. .. .. .. | 11·0 | 750 | 1924 | Municipality |
| *Wales* | | | | |
| Cwm Dyli .. .. .. | 1 130 | 5 500 | 1906 | North Wales Power Co. |
| Dolgarrog .. .. .. | 1 000 | 15 400 | 1907<br>1925 | |
| Maentwrog .. .. .. | 650 | 24 000 | 1928 | |
| *Scotland* | | | | |
| Foyers .. .. .. .. | 1 000 | 5 000 | 1896 | British Aluminium Co. |
| Kinlochleven .. .. .. | 900 | 23 000 | 1909 | |
| Bonnington .. .. .. | 174 | 9 840 | 1926 | Clyde Valley Electrical Power Co. |
| Stonebyres .. .. .. | 91 | 5 680 | 1926 | |
| Lochaber .. .. .. | 800 | 33 000–75 000 | 1929 | British Aluminium Co. |
| Rannoch .. .. .. | 465 | 32 000 | 1930 | Grampian Electricity Supply Co. |
| Tummel .. .. .. | 160 | 34 000 | 1933 | |
| Loch Luichart .. .. .. | 110 | 1 200 | 1920 | Ross-shire Electric Supply Co. |
| †Glenlee .. .. .. .. | 360 | 24 000 | — | Galloway Power Co. |
| †Tongland .. .. .. | 102 | 33 000 | — | |

* Locations shown in Fig. 1.

† Under construction.

So far as it has been investigated, the economic margin in favour of tidal-power developments is relatively small, and, while in the interests of the conservation of our coal resources such developments should be encouraged, it is doubtful whether the present state of the power-supply industry in this country justifies proceeding with any large-scale development of tidal power. In the future progress of our power policy, however, power derived from the tides will no doubt merit consideration and form an important factor in a general programme of electrification.

### THE GRAMPIAN SCHEME.

The general considerations relating to hydro-electric development in the British Isles have been dealt with, and brief reference has been made to the various developments which have either taken place to date or are in contemplation. It is now proposed to deal in detail (so far as is possible within the limits of this paper) with the Grampian development of the Grampian Electricity Supply Co.

The powers obtained under the Grampian Electricity Act of 1922 cover the works which have been carried out. These powers were the culmination of a series of promotions, commencing as far back as 1912, the detail of which is outside the scope of this paper. Briefly, the works cover the utilization of the waters of Loch Ericht and Loch Rannoch and their respective watersheds, and the deviation of certain other watersheds into Loch Ericht, principally the River Truim, Loch Seilich, and Loch Garry. These proposals can be noted from a reference to Fig. 2. The Act of 1922 also provides for further developments on the River Bruar, but as no construction has so far taken place in connection with them it is not proposed to deal with them in detail.

The area of the watershed covered by the Ericht section is 185·2 square miles and that of Rannoch 200·7 square miles, with average rainfalls of 70 in. per annum and 50 in. per annum respectively. The head of the former development is 485 ft. and that of the latter 167 ft., which on a continuous basis would give 26 000 b.h.p. at the Rannoch station and 19 000 b.h.p. at Tummel.

It will be appreciated that the amount of power capable of development in any individual catchment area is dependent on the amount of storage available in relation to the yearly distribution of the run-off. In this respect the catchment area of Loch Ericht is very favourable, as facilities for storage are exceptional on account of the natural configurations of the area. Consequently, powers were obtained under the Grampians Act to vary the level of Loch Ericht between Ordnance datums 1 128 and 1 205. While the Act thus authorizes the raising of the level of the loch by 52 ft., the requirements of the completed scheme to obtain the most economical development necessitate the raising of the level by 25 ft. only, or up to datum 1 178, which will create sufficient reservoir capacity to meet the demand of the full development. The Act, however, does not permit any artificial variation in the level of Loch Laidon, and at Loch Rannoch storage is only available between the levels 672 and 664 ft.; this is totally inadequate to compensate completely for the water flow from this catchment area for power purposes. It is in this connection that the value of a comprehensive scheme must be emphasized. In the present lay-out the ultimate development of the whole watershed has been kept in view. By interlinking the two power stations to operate in parallel, and distributing the output according to the varying conditions of flow in the two catchment areas, it will be possible to utilize Loch Ericht as an impounding reservoir for the whole watershed, thus permitting the most economic and rational development of the available resources. This would not have been possible if the catchment areas of Loch Ericht and Loch Rannoch respectively had been treated as individual developments, or had been only partially developed without consideration of the ultimate power possibilities of the whole watershed.

In arriving at the best method of co-ordinating the respective watersheds and determining the economic limit of maximum power to be developed in any of the stations, all the factors of maximum and minimum water flow and its variation throughout the year in combination with maximum peak loads, load factor, and diversity factor, had to be taken into consideration and carefully investigated. The guiding principle, however, was that in times of flood the Tummel station would take the base load, and storage would be effected at Loch Ericht; and vice versa during low-water periods. For that purpose the capacity of the respective works has been determined according to a definite ultimate scheme of development, in order that the maximum power that could economically be developed might be available for commercial use. As a result, the works in connection with Loch Rannoch power station have been designed for an ultimate capacity corresponding to an output of 66 000 h.p. Power units of 44 000 h.p. are already installed in the present generating station, and have been commercially operated since November 1930. The second stage of the development, comprising the power station on the River Tummel, is designed for an installed capacity of 44 000 h.p. Thus the power units installed in the two generating stations will ultimately aggregate 110 000 h.p.

The output at the present stage of the combined development is approximately 55 000 h.p., but when the full storage is provided the total output will be approximately 80 000 h.p. on a 50 per cent load-factor basis.

In addition to the normal requirements of the development of the Grampian area itself, the promoters had it primarily in view originally to supply the electricity requirements of the Fife Electric Power Co. and the Scottish Central Electric Power Co., but owing to the passing of the 1926 Act and to the power stations of these companies being selected stations for the purposes of the Act, power to the extent of 24 000 kW is being supplied to the Central Electricity Board for general purposes instead of to these two power stations.

The Grampian Electricity Supply Co. is rapidly developing its own area as originally authorized by the Act of 1922 and as extended by the Scottish Highlands Order, 1932, the connected load being about 25 000 kW and the maximum demand 6 000–7 000 kW.

### *Loch Ericht Development: Civil Engineering Works.*

The general lay-out of the work covered by this part of the scheme can be gathered from the diagrammatic plan and profile shown in Fig. 3, and will now be briefly described. The level of the loch on the initial development can be varied to a total depth of 17 ft., which gives a reservoir capacity of 3 425 million cub. ft.

*Diversion works.*—As has already been stated, the Grampian Act authorized the diversion into Loch Ericht reservoir of the water from certain adjacent watersheds. Under the present scheme the River Truim and the Allt Ghlas stream have been diverted to augment the water supply to this reservoir.

*Dam.*—The dam as constructed provides for an immediate level in Loch Ericht of 1 165 ft. Ordnance datum, and ultimately, on the full development, for a level of 1 178 ft. Ordnance datum, the minimum draw-off level being 1 148 ft. Ordnance datum. The dam has a total length of 1 402·5 ft., and consists of a gravity section on the east side, where the foundations were suitable, while on the west side a core wall with earth embankments was provided. The dam rises to a height of 45 ft. above the river bed. There are two lines of openings; the lower set is for the present development and will be filled up when the water level is raised to its maximum.

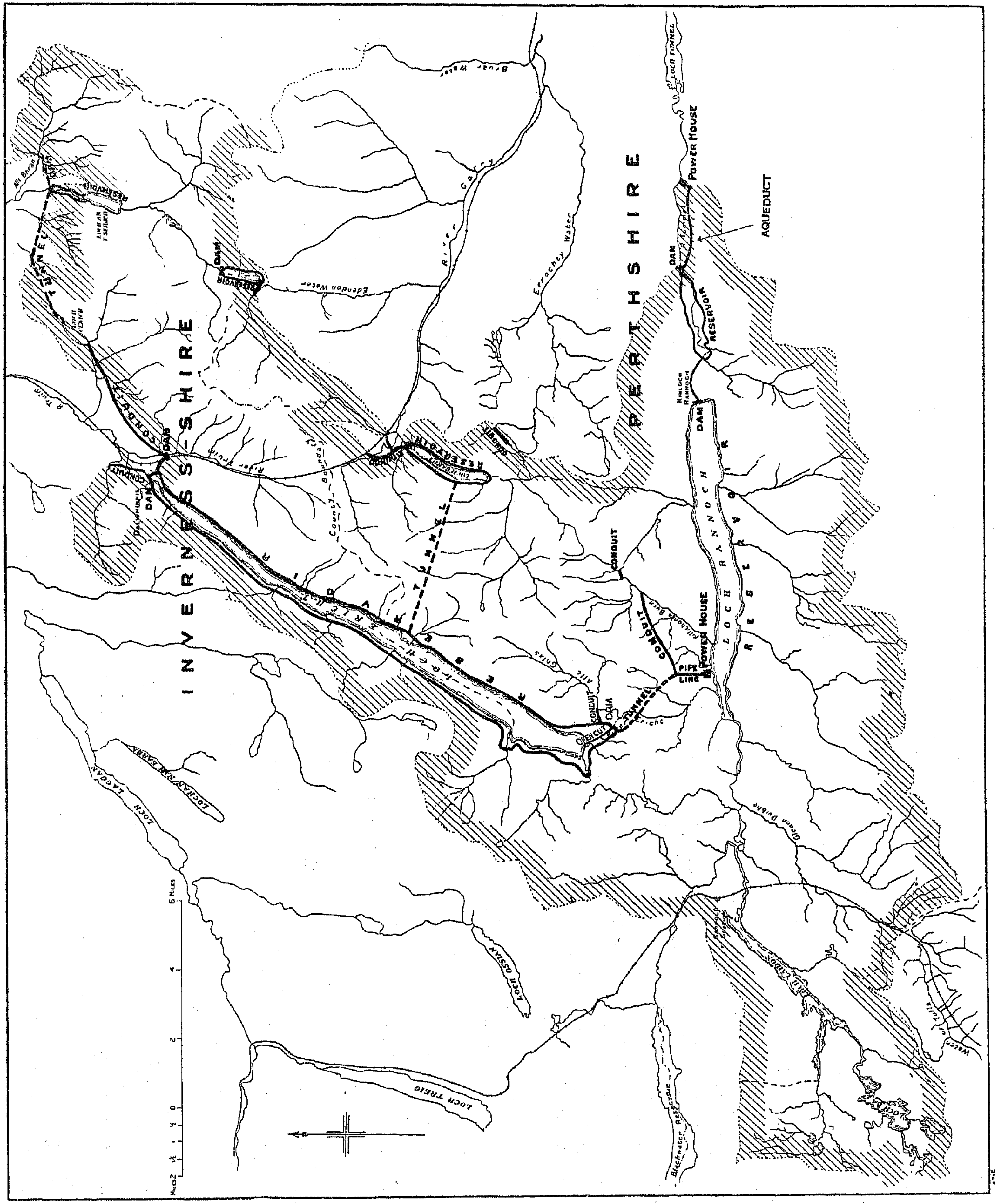

FIG. 2.—Map showing the Grampian hydro-electric power schemes.

*Intake.*—The intake is 18 ft. in diameter and extends to a point 65 ft. 6 in. below the invert of the channel. It is concrete-lined and extends above the water level as a concrete tower, access being obtained from the roadway over the dam by means of a steel-girder bridge. Water is always drawn off below the surface; this prevents driftwood, etc., from reaching the screens. The screens are in duplicate, one always being in position while the other is being cleaned. The bottom of the intake shaft joins with the tunnel and is fitted with a roller-type gate of a new design.

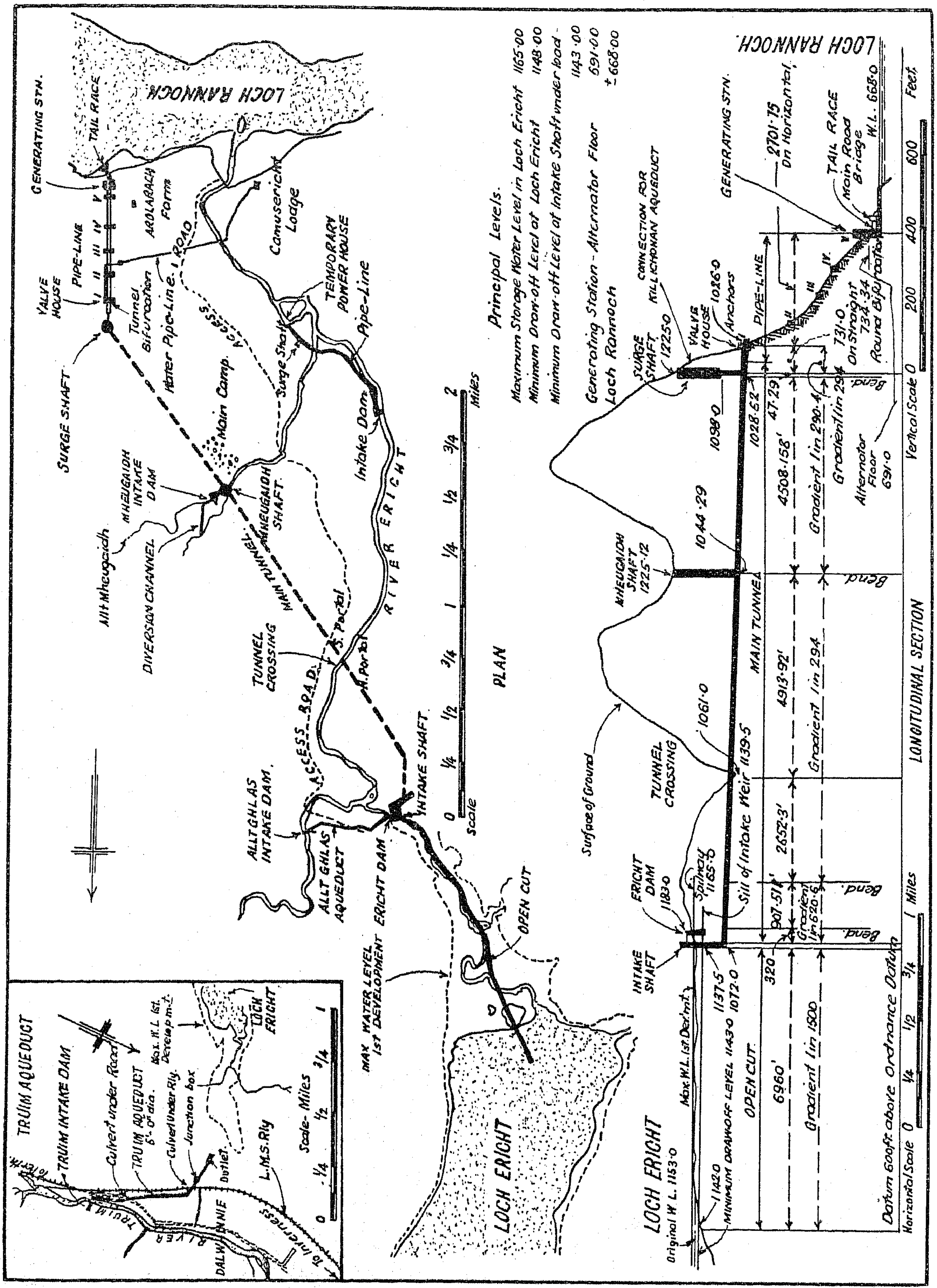

FIG. 3.—Diagrammatic plan and profile of Ericht scheme.

*Main tunnel.*—From the intake tower the tunnel crosses below the foundations of the dam, and, after a short deviation from the river to obtain adequate cover, runs in a straight line to the surge shaft for a total distance of 14 080 ft., including the last portion of 288 ft. which is bifurcated for connection to the valve house at the outlet end of the tunnel. The tunnel has a cross-sectional area of 120 sq. ft. and is designed to carry a maximum of 1 440 cub. ft. per sec., which corresponds to a water velocity of 12 ft. per sec. The section is horseshoeshaped, with a height of 11 ft. 7$\frac{13}{16}$ in., and along its entire length is lined with concrete in order to present as smooth a surface as possible to the water and reduce frictional resistance. Where the tunnel route crosses the River Ericht the water is conveyed in a riveted steel pipe-line, 11 ft. 10 in. diameter, connecting the tunnel portals at each bank of the river.

*Mheugaidh shaft and intake.*—For the purpose of diverting the Mheugaidh stream into the tunnel, a shaft was constructed 154 ft. deep and of an oblong section measuring 15 ft. by 13 ft. The water is conveyed down the shaft through a concrete pipe 3 ft. diameter; and an air vent 2 ft. diameter, also in concrete, has been provided. A concrete diversion dam of gravity section has been constructed across the stream and combined with an intake chamber, from which the discharge is directed through a circular reinforced-concrete conduit, also 3 ft. diameter, to the shaft for a distance of 525 ft.

*Surge shaft.*—The surge shaft is a vertical circular shaft, just over 196 ft. deep, sunk in the solid rock. It is 12 ft. in diameter for the lowest 70 ft. of its depth, the upper portion being increased in diameter to 45 ft. The top is at a height of 1 225 ft. over datum, which is the same level as that of the top of the Mheugaidh shaft.

*Valve house.*—At a distance of 385 ft. from the surge shaft the tunnel divides into two parallel branches—circular in section and of 10 ft. 6 in. diameter—for a total length of 720 ft., terminating in a breeches pipe in each section at the valve house, from which point two 8-ft. pipe-lines convey the water to the power station on the shore of Loch Rannoch. The two outlets from the tunnel at present utilized are each controlled by one hand-operated and one hydraulically-operated throttle valve. The latter valve is actuated by oil pressure from accumulators, which are charged by an electrically-driven oil pump also equipped with a Pelton-wheel-operated emergency pump. The hydraulic valve is arranged for automatic closing in case of a burst in the pipe-line, and can also be operated from the power house by an electrical remote control. The equipment at the valve house includes automatic air valves to admit air to the pipe-lines immediately the valves are closed. Provision has also been made in the valve house for receiving a third pipe-line, required for completing the final section of the development.

*Pipe-lines.*—For the purpose of the present scheme two pipe-lines have been installed, each having an external diameter of 7 ft. 10½ in. and a total length, from the control valves at the top to the inlet valve at the power house, of 2 728 ft.

One interesting feature of the pipe-line is the method adopted for the supports. Owing to the comparatively large stresses involved, which had to be taken up by the five anchorages provided in each line, the usual method of supporting each pipe on a concrete base or pedestal was discarded. Instead, each pipe-line is carried on intermediate roller supports, spaced at an average distance of 48 ft., and it was thus possible to effect considerable economies in respect of the anchorages owing to the reduced volume of concrete required. Below each anchorage an expansion joint of the stuffing-box type was provided, as well as manholes to give access to the interior of the line. After erection the interior of the pipes was scraped and a rust-preventing solution applied cold, this being finally covered with a bitumastic enamel applied hot.

### *Loch Ericht Development: Power House and Equipment.*

*Building.*—This is steel-framed and has walls composed of pre-cast concrete blocks, every endeavour being made in the design to harmonize with the immediate surroundings. The power house (Figs. 4 and 5) measures 95 ft. by 60 ft. and is 44 ft. in height from the generator floor level. A wide gallery containing the controlling switchgear runs at a height of 20 ft. above the floor level, and is reached by means of two staircases. An electrically-operated travelling crane with a lifting capacity of 50 tons runs the whole length of the machine bay, which at present contains two generator sets, with foundations for a further set to be installed later. The whole structure is founded on solid rock, and the suction tubes from the turbines are enclosed in the concrete foundations and discharge into the tail-race, which joins Loch Rannoch at a distance of 540 ft. from the power house.

*Turbines.*—Two generating units have so far been installed, each composed of a vertically arranged Francis turbine enclosed in a spiral casing. This arrangement was decided upon after due investigation of the relative merits of the horizontal and vertical settings had shown the latter to require the less space and consequently to give a cheaper and more compact lay-out of the power house. The turbines have been designed for the conditions under which they will operate when the level of Loch Ericht is raised to 1 178 ft. Ordnance datum, the level required on the completion of the final section of the scheme. Each turbine is therefore designed to develop its full output of 22 000 h.p. under a net head of 515 ft. at 500 r.p.m. and a maximum static head of 541 ft. The net head will vary down to a minimum of 396 ft., depending on the water level in the Ericht reservoir, the output under the minimum head being 15 000 h.p. On account of the varying head under which the turbines will operate, it was specified that the maximum efficiency should be secured at 80 per cent of full load, at which an efficiency of 90·5 per cent was guaranteed.

The turbines are of standard design, housed in a cast-steel spiral casing, which is provided with external regulating of the guide apparatus and embodies special break links to protect the guide vanes from damage by any obstruction which may be carried down to the turbines. The material selected for the runner was special alloy bronze, which it was considered will best withstand pitting or erosive action due to cavitation. All the other parts of the turbine exposed to the action of water under high velocity are provided with renewable liners of cast steel. In order to minimize the effect of cavitation on the runner the suction head was reduced as far as possible, the maximum being 12 ft., reckoned from the centre of the inlet. Provision is made for the easy dismantling of the runners, and the accessibility of all parts of the turbine is the keynote of the design.

Each turbine is equipped with an oil-lubricated guide bearing on top of the casing, the weight of the rotating parts and the hydraulic thrust being carried by the thrust bearing on the top of the alternator. The oil-

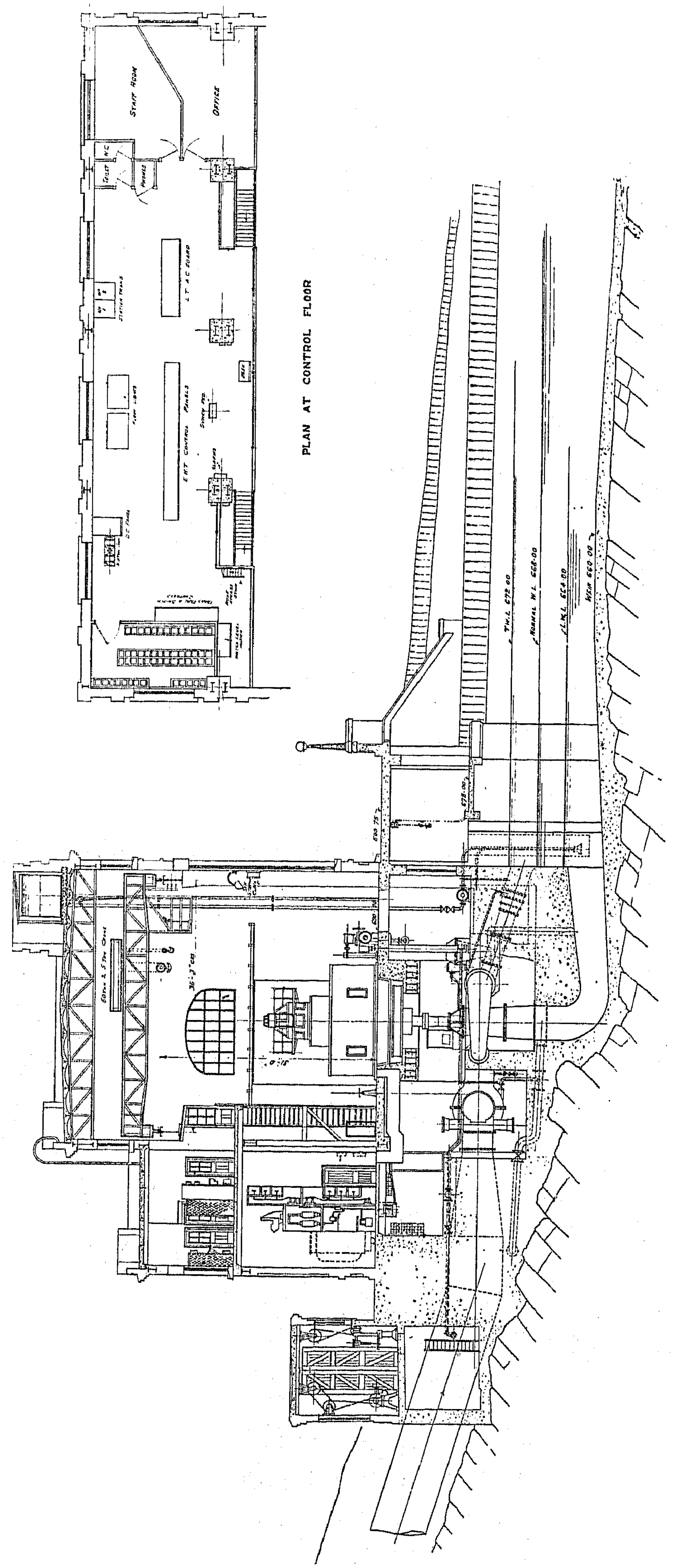

FIG. 4.—Rannoch power station: cross-sectional view.

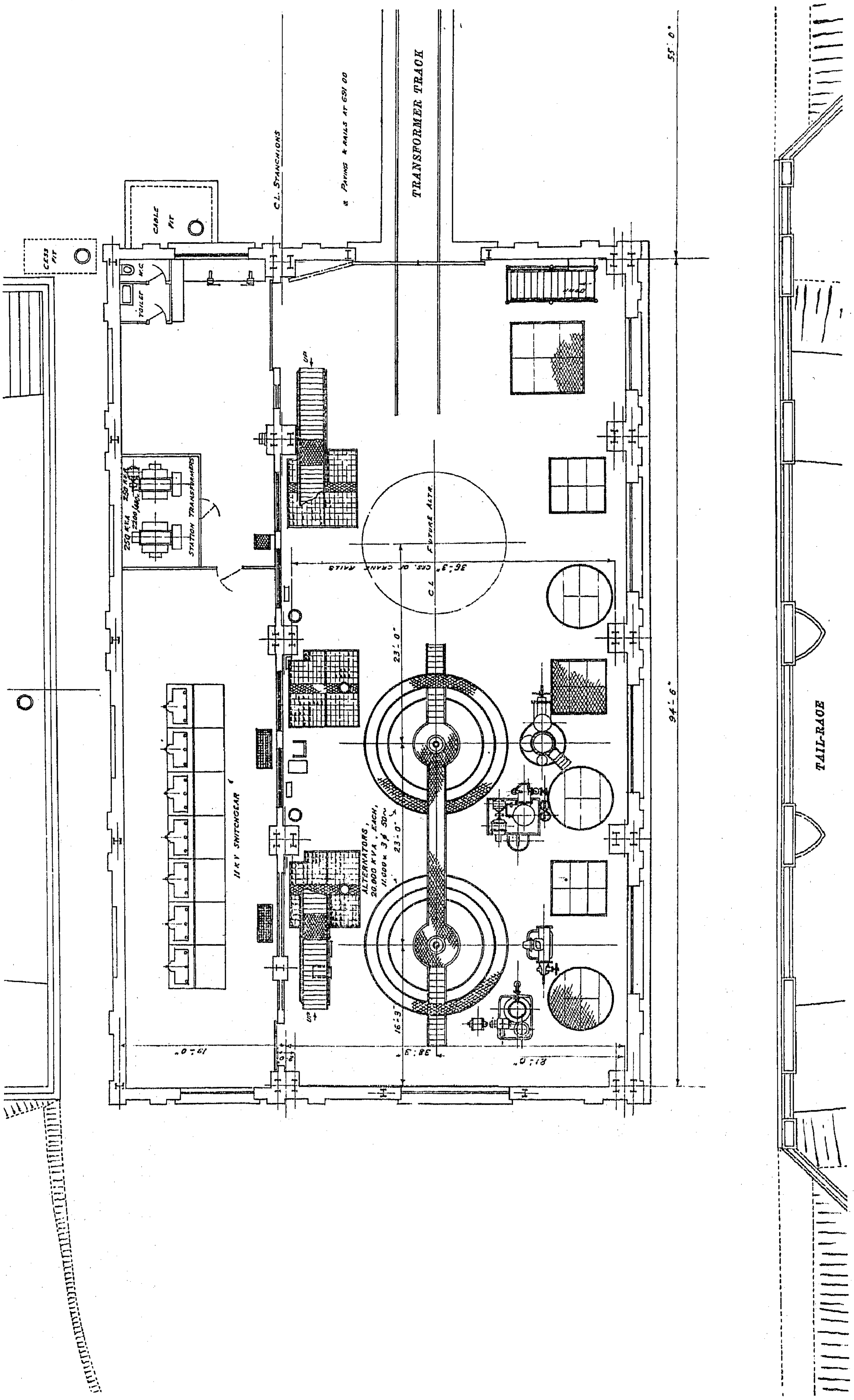

FIG. 5.—Rannoch power station: plan on alternator floor.

### *Loch Rannoch Development: Power Station and Equipment.*

*Building.*—This is a steel-framed structure contained in pre-cast concrete-block walls (Figs. 7 and 8), the whole design having a simple dignity which fits in well with the surrounding natural features. The walls are built of pre-cast concrete blocks, spaced at about 4 in. to 6 in. apart. In connection with this part of the works it is of interest to note that 166 different types of blocks, totalling 47 000 blocks, were actually used in construction. The building is 175 ft. long, 90 ft. wide, and 50 ft. above the floor-level. There is no basement proper, but incorporated in the foundations are the necessary air ducts, cable trenches, and flood-water channels, to all of which access is provided. The switchgear is housed in a compartment on the floor-level, and the whole of the control gear, battery, offices, etc., are on one floor

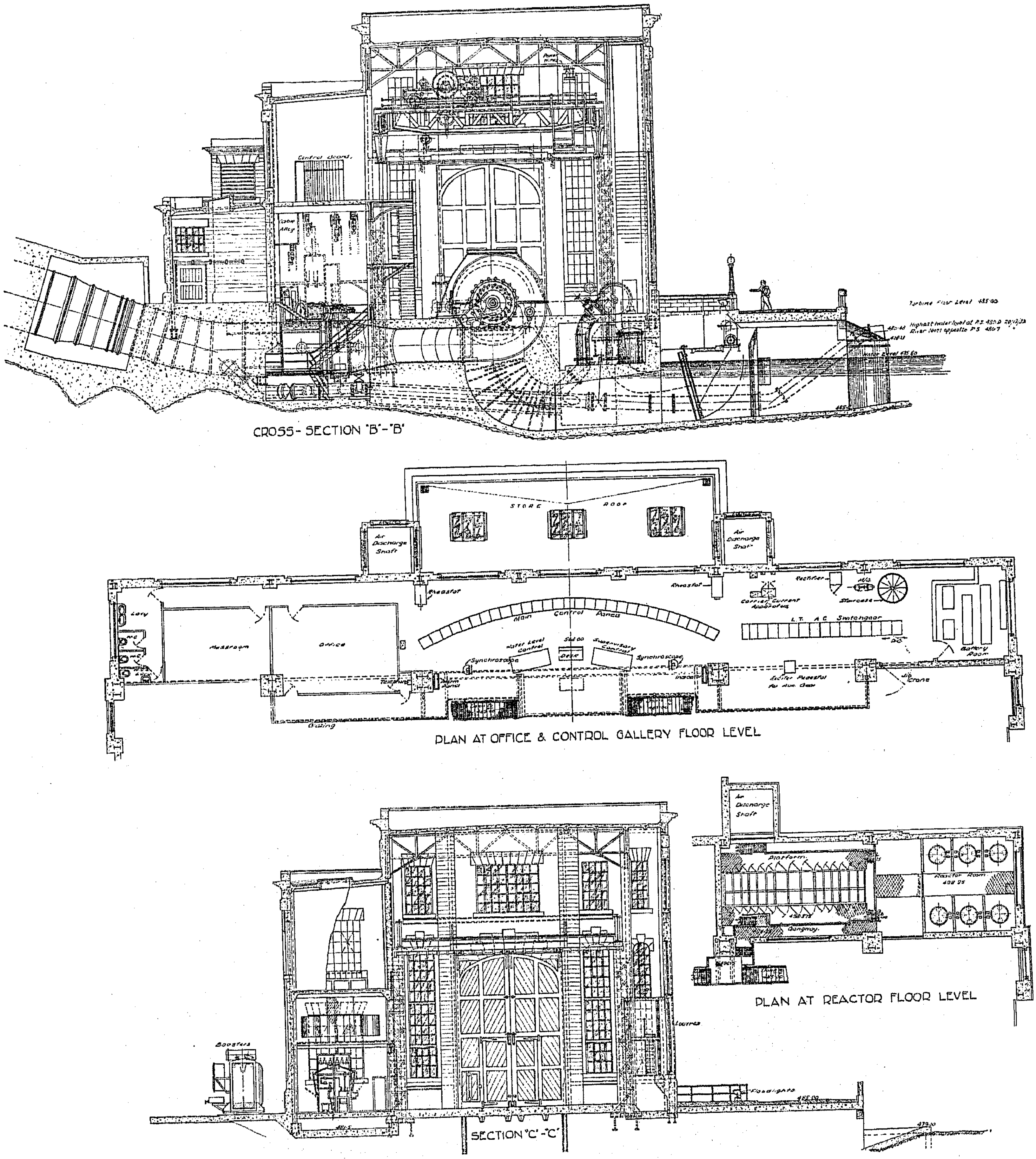

FIG. 7.—Tummel power station: cross-sections, and also plan on control gallery.

above, which is reached by two main staircases. The station is equipped with an electric travelling crane, the capacity of the main hoist being 120 tons and of the auxiliary 15 tons. The main door is 20 ft. wide by 29 ft. high, these dimensions being necessary to admit the step-up transformers and for the purpose of mounting insulators, carrying out overhauls, etc.

*Turbines.*—The machine equipment consists of two main turbines and one auxiliary, all of the horizontal Francis type. The complete installation has been provided, no further extension being necessary.

The main turbines are each of 22 000 h.p. (24 000 h.p. overload rating), double-runner, with twin cast-iron spiral casings and single discharge. The normal speed is 300 r.p.m. with a head of 160 ft. The runners are composed of chromium stainless steel and are the first

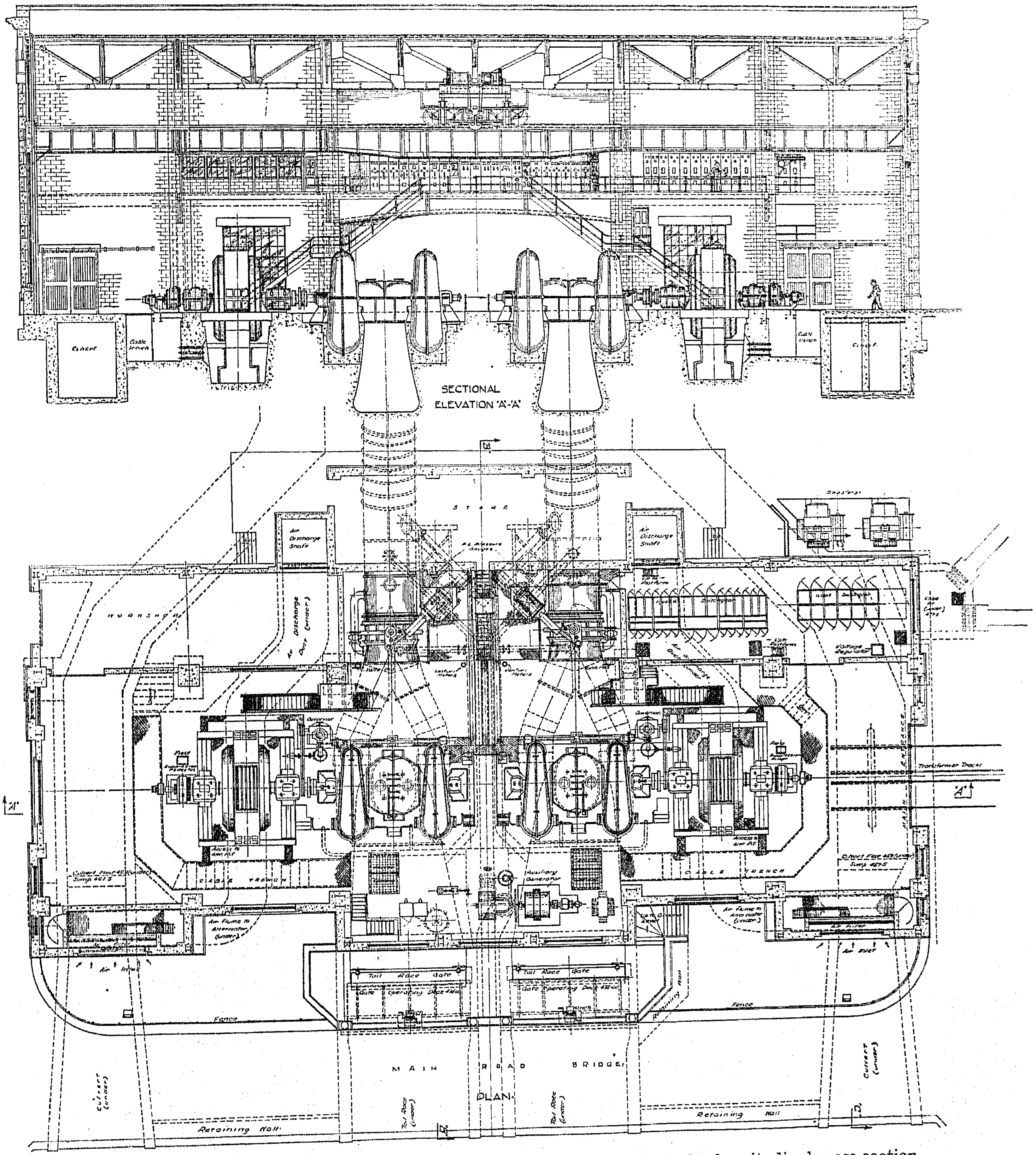

FIG. 8.—Tummel power station: plan on alternator floor, and also longitudinal cross-section.

castings of so large a size to be made in this country of such material. This choice of material was made as presenting greater resistance to cavitation than either gun-metal or cast steel, and it enabled the centre line of the shaft to be placed about 4 ft. higher above tail water-level than would have been possible with the last-named material. The guide apparatus consists of the usual series of streamline-section vanes in cast steel, connected to operating rings mounted on a roller train which is in turn actuated from the governor. The vane links are designed to break as soon as the load exceeds a predetermined figure, and care has been taken to ensure that when a link is broken its vane cannot be jammed. The shaft is hollow and is connected to the alternator by a coupling, power being transmitted through the face key and not the bolts, the latter serving to hold the coupling faces together only. The turbine is carried in two main bearings, ring-lubricated, the sump being water-cooled. A small Michell thrust bearing is provided at the end of the shaft to take up any slight out-of-balance under starting or running conditions. The plant is so arranged that the alternators can be run as synchronous condensers if desired, the turbines being either coupled to or uncoupled from them as desired. The governor is of the oil-operated type, with double compensating gear to prevent hunting. The pendulum movement is utilized to actuate a valve regulating the supply to a servo motor, and in conjunction with the control gear a very efficient lay-out has been devised. The intention is primarily to make the running of the plant as automatic as possible, so that once started up the alternators may be self-synchronizing on to the busbars, if desired, and will remain on a fixed load or vary it within predetermined limits. Provision has also been made to take care of conditions arising from a run-away or from the breaking of the governor belt. The air vessels of the two machines are interconnected so as to safeguard the supply of oil to the governor for quick-starting purposes on the stand-by machine. The governor generally is arranged so that no direct manual operation is required, the whole control being from the switchboard gallery. The equipment is of special interest, and will be dealt with in detail under the heading of " Load Control."

The main inlet valves are of the butterfly type, 10 ft. in diameter, and are controlled by hydraulic pistons actuated by the pipe-line water pressure. They are designed for opening by hand, and normally remain open, but under emergency conditions they can be quickly closed either by the overspeed device or by push button.

The auxiliary turbine is a unit of 400 kW capacity which was originally used in the temporary power station for construction purposes, and is installed as an emergency local supply unit.

*Alternators.*—The main electrical generating equipment consists of two horizontal alternators, each with a maximum continuous rating of 17 000 kW, coupled to the above turbines. There is no independently-driven auxiliary plant in the station, each turbo-alternator unit being entirely self-contained. The machines will deliver 21 250 kVA at 0·8 power factor lagging, at voltages between 11 000 and 13 000 volts, 50 cycles per sec., 3-phase. A maximum voltage of 15 600 volts can be withstood for 5 minutes; this extra rating would safeguard the machines during the period before the field suppression could act, which might happen in the event of excessive speed variation resulting in abnormal electrical conditions. The above kVA rating is obtained down to a power factor of 0·65 leading, and for line-charging purposes the machine could deliver about 15 000 kVA at zero leading power factor.

The shaft is supported on two main and one outer bearings, all being water-cooled. The weight of the alternator shaft and rotor is 117 tons, and the total weight of the turbine and alternator rotating parts is 137 tons.

As already mentioned, the machines may be run as synchronous condensers and, for starting-up purposes, the bearings can be supplied with high-pressure oil, so as to reduce the starting torque.

The excitation arrangements are similar to those described for the Rannoch machines, but the voltage regulation is of a later type which readily lends itself to the control of a large excitation range. It is primarily a combination of an automatic motor-operated field rheostat with an improved arrangement of under- and over-excitation relays similar to those at Rannoch.

*Ventilation.*—This is effected through ducts supplying 55 000 cub. ft. of air per minute. The inlet air passes through filters, and after being drawn through the machines can be discharged either into the buildings or outside as desired, regulating louvres making this possible.

*Switchgear.*—The main switchgear is of the cellular type, equipped with single busbars at the moment, but capable of duplication if found desirable or necessary later. There are four main oil switches, motor-operated, each of 750 000 kVA rupturing capacity, controlling the machines and the 11/132-kV step-up transformers. The station is also required to supply power to the 33-kV system, and for this purpose an auxiliary 11 000-volt board is connected to the main board through reactors, which reduce the rupturing capacity of the auxiliary-board oil switches to 150 000 kVA. This switchgear is of the steel-cubicle type and is mounted in the compartment adjacent to the main cells as shown in Fig. 8. The voltage on this board is controlled by automatic tap-changing boosters with a 20–25 per cent range, so that the supply for the board may be varied independently of the main busbar voltage. This arrangement is necessary as the 11/33-kV distribution transformers are connected to and controlled from this board, as well as the local 11-kV distribution. The 400-kW auxiliary alternator can also be connected to supply this board independently of the main alternators.

The 440/250-volt supply for station and local-supply purposes is derived from tertiary windings on the 11/33-kV step-up transformers, and its control board, which also carries the battery control, is mounted on the main gallery adjacent to the main control panels of the station. The duplicate 440-volt supply is controlled by automatic reclosing selective switches; this arrangement enables continuity of the l.t. supply to be safeguarded without any direct connection to the main busbars of the station, and eliminates the necessity of separate station transformers. The arrangement of the low-tension a.c. and d.c. gear is shown in Fig. 7, to the right of the main switchboard. It will be observed from Fig. 7 that the 110-volt tripping battery and its charging apparatus are also located on this floor.

*Substations.*

A brief description will now be given of the Rannoch, Tummel, and Abernethy, step-up and switching substations and their connecting lines. The diagrammatic lay-out of the system as a whole is shown in Fig. 9, and the arrangement of the various substations is indicated in Figs. 10–15.

(*a*) *Rannoch.*—Dealing first with Rannoch, the alternators are connected through underground cables with the outdoor substation, located on a site adjacent to the power house, where the 11-kV power is stepped up to 33 and 132 kV respectively. Power is then transmitted along a 4-circuit overhead line, which will be referred to later. The 132-kV substation (Fig. 10) is equipped with two 20 000-kVA delta/star-connected transformers of a nominal ratio of 11/132 kV. They are forced water-cooled, and a stand-by supply is obtained from a tank on the roof which is kept supplied by pumps drawing from the tail-race. An additional stand-by can be obtained from the main pipe-line. The transformers are designed to work with the neutral point unearthed. The end turns are specially reinforced, the designed test voltage being 291 kV for 1 minute. No tappings are provided; it was desired that the transformers should be of the simplest and most rugged construction, so that they could be regarded as part of the transmission lines. These transformers are connected in series with boosters having a voltage range of adjustment of ± 10 per cent, the boosters being of the on-load tap-changing type and operated by remote control from the switchboard gallery in the power station. Each booster is specially reinforced to withstand normal voltages up to 160 kV, and is also designed for a test voltage of 321 kV. Provision is made in the substation for the addition of 132-kV automatic oil switches, but in the meantime the whole of the power switching is carried out on the 11-kV side. Air-break switches are used on the 132-kV side for disconnecting the transformers and boosters. These are suitable for breaking the magnetizing current, but not for breaking load. The neutral of the 132-kV system is earthed through a resistance which limits the maximum earth-fault current and the severity of faults to earth. At the same time, the resistance also serves to limit the maximum fault current to a value below that which would induce a dangerous voltage in the Post Office telephone lines in the area.

The 33-kV substation is equipped with two 5 000-kVA star/star-connected transformers fitted with tap-changing gear of the Stragiotti type controlled by oil switches on the main 11-kV board. These transformers are provided with tertiary windings, which provide the source of the 2 200-volt supply previously referred to. Provision is made for the addition of future 33-kV oil switches, but all switching for the time being is done by means of air-break switches on similar principles to those adopted in the 132-kV substation. The neutral point of the 33-kV system is also earthed through a resistance, the fault current being limited to a value of approximately 100 amperes. The outdoor constructional work of the substation is of fabricated steel encased in concrete, which provides a weatherproof construction and requires little maintenance.

(*b*) *Tummel.*—The arrangements at Tummel differ considerably, owing to the site conditions and also to the duty required from the various sections of the apparatus. Fig. 11 shows the general lay-out. It will be noted that the substation is in two parts, one consisting of a step-up substation and the other of a switching station at the junction with the main transmission lines.

The alternators are connected through underground cables with the step-up substation, where the 11-kV power is stepped up to 33 kV and 132 kV respectively. Fig. 12 illustrates the lay-out. The 11/132-kV transformers are each of 21 000 kVA capacity, plain water-cooled, the coils being situate in the upper part of the transformer and supplied with a gravity supply of water from the main pipe-line. They are delta/star-connected without tappings, and each is designed to deliver continuously the full output of one alternator under busbar voltages varying from 11 to 13 kV. The 132-kV windings are fully insulated throughout, and each end of the winding is specially reinforced, the whole being tested to 300 kV to earth. In the event of failure of the water supply, these transformers will carry full load for a period of 20 minutes. Air-break switches are used for disconnecting purposes only, all power switching being done on the main 11-kV board. The neutral can be earthed through a resistance as at Rannoch, or a potential transformer can be introduced for protective purposes.

The 33-kV step-up is also carried out in the same substation. The equipment consists of two 5 000-kVA units, oil-cooled, star/star-connected, and provided with a delta tertiary winding designed for 440 volts. The insulation particulars compare proportionately with those for the main units. The 33-kV system can be earthed through a resistance or a potential transformer, and, as has been previously mentioned, automatic tap-changing boosters are provided on the 11-kV supply side.

The power is supplied to the switching station (Fig. 13) by means of a single span of about 1 500 ft. carried on steel towers, the construction being generally as described below for the main transmission lines. The switching station is divided into two parts, one for 132 kV and the other for 33 kV. The former provides for the junction with the line coming from Rannoch, this being effected by connecting one of the original spans of that line on to duplicate busbars. Air-break switches are provided on the main lines for isolating purposes. Two of these switches are motor-operated, and so controlled that they can only be operated when no current is passing.

The 33-kV lines from Rannoch are looped in to the switching station, and similar switches are provided so that, if desired, the 33-kV lines from Rannoch can be cut out and the whole supply given from Tummel.

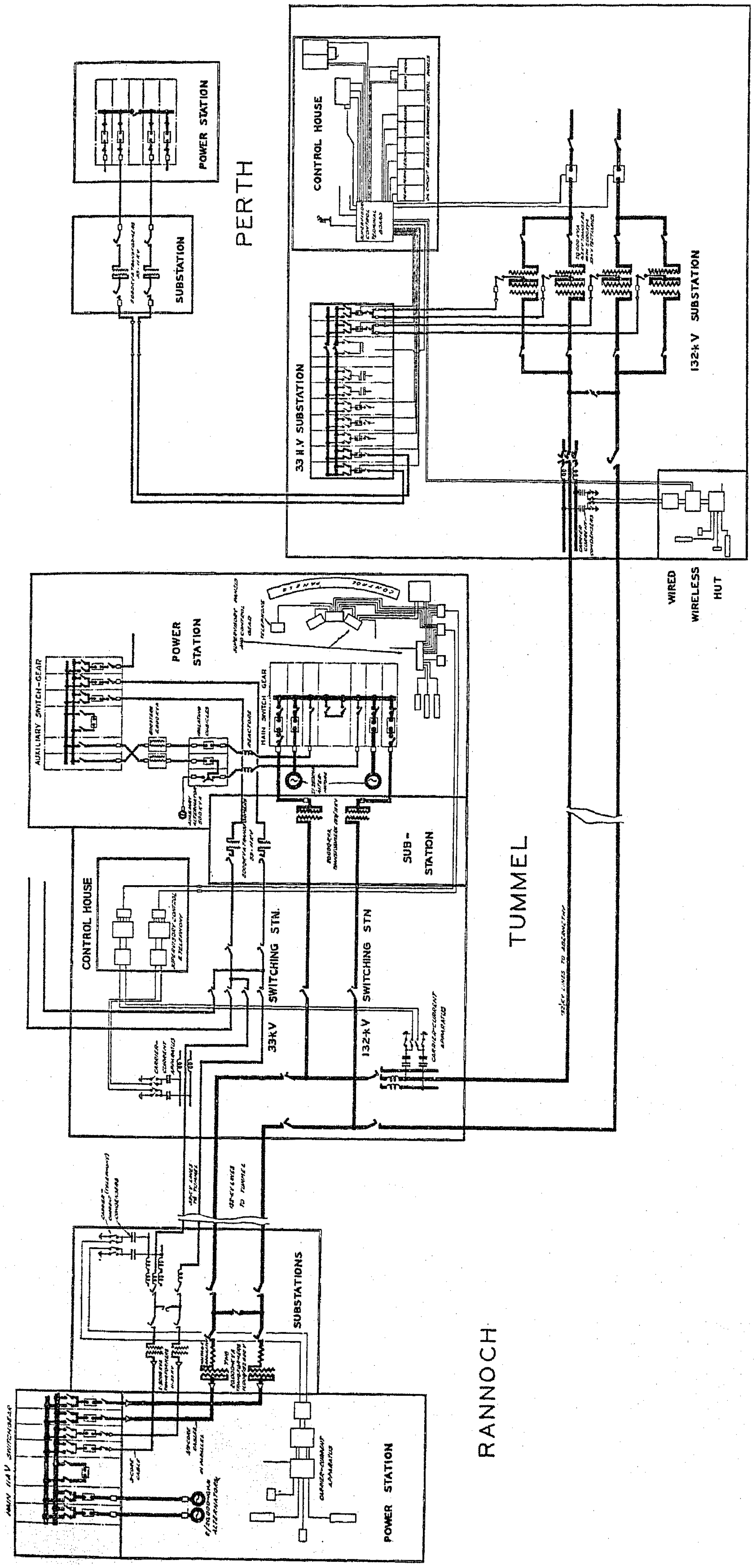

FIG. 9.—Diagrammatic system lay-out of Rannoch–Tummel–Abernethy.

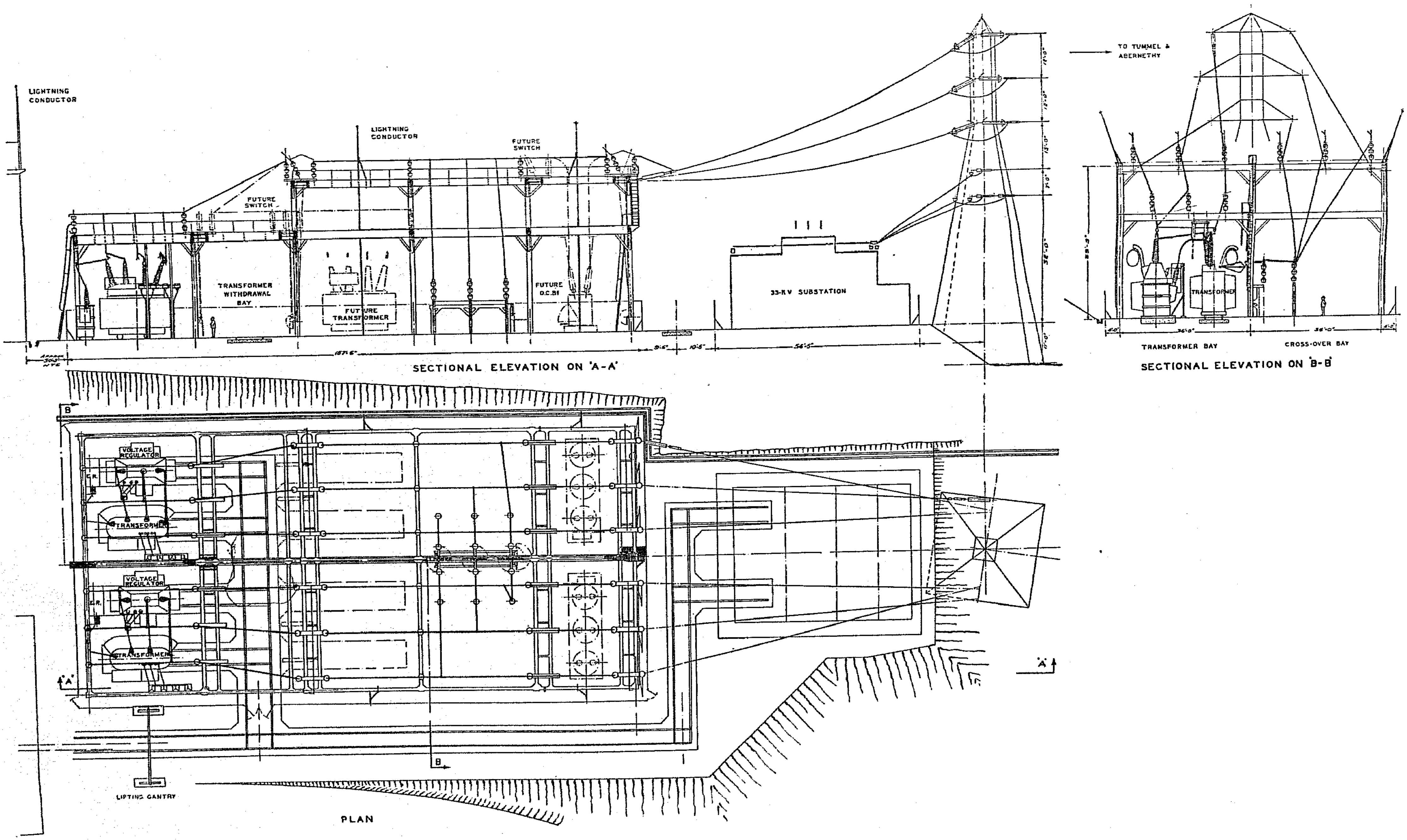

FIG. 10.—Arrangement of Rannoch outdoor step-up substation, 11 000–132 000 volts.

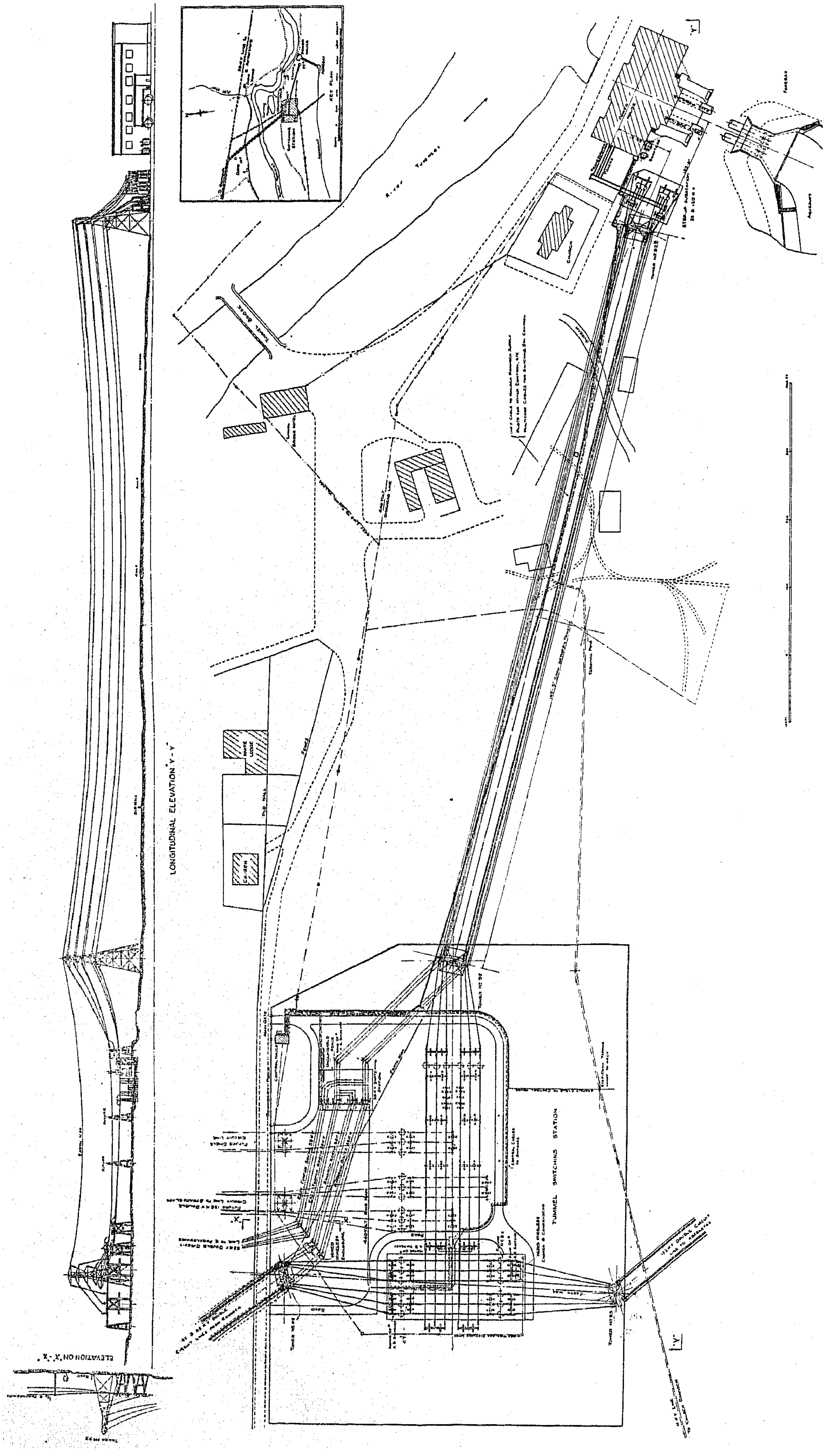

FIG. 11.—Site plan of Tummel Bridge power house, substation, and 132-kV and 33-kV switching station.

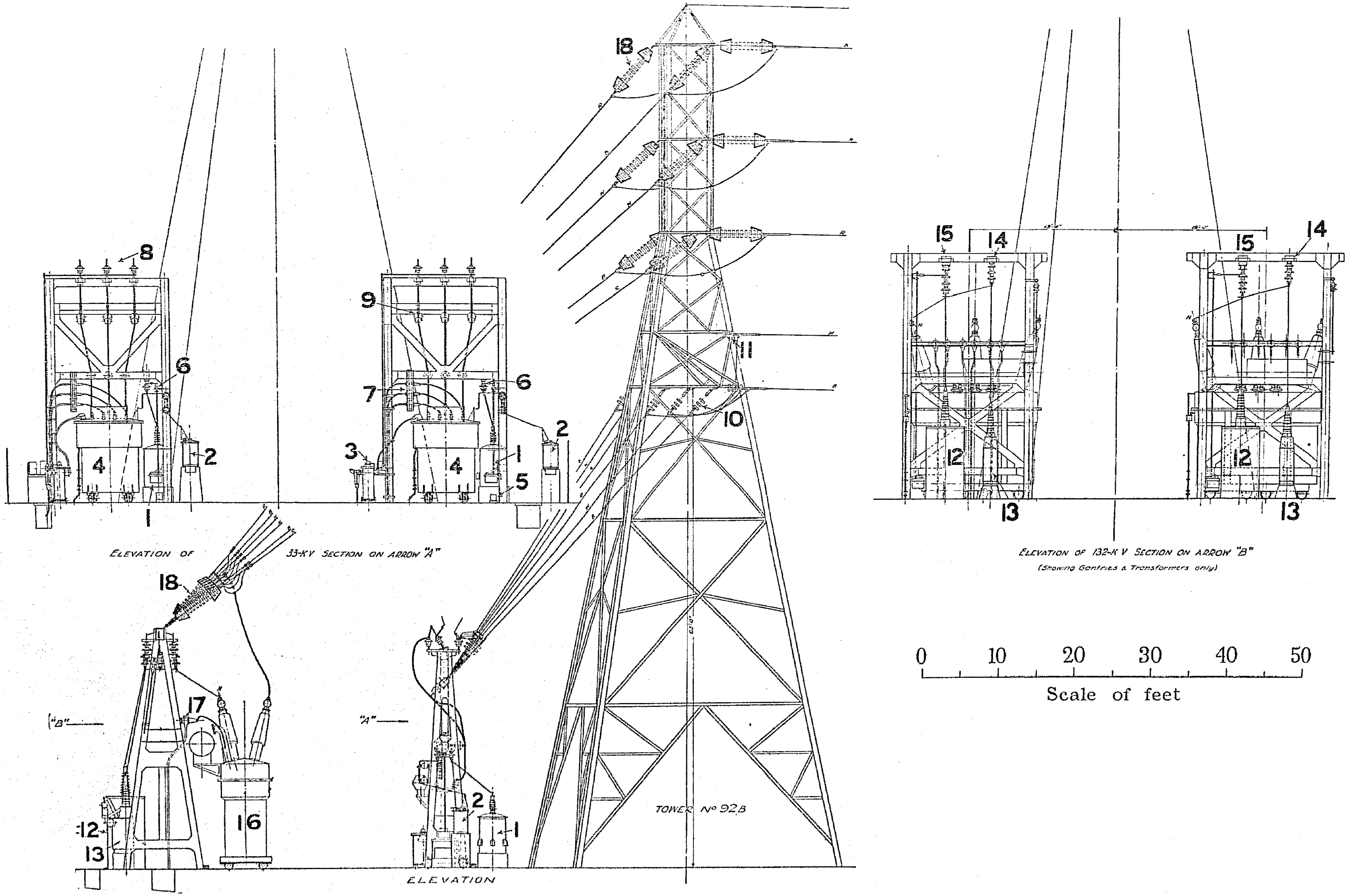
18
8
9
6
7
6
2
4
2
3
4
1
2
5
1
11
10
15
14
15
14
12
12
13
13
Elevation of 33-kV Section on Arrow "A"
Elevation of 132-kV Section on Arrow "B"
(Showing Gantries & Transformers only)
18
17
16
12
13
"B"
"A"
2
1
Tower No 92B
Elevation
0
10
20
30
40
50
Scale of feet

FIG. 12.—General arrangement of Tummel step-up substations (11 kV–33 kV, and 11 kV–132 kV).

1. Earthing resistance.
2. Potential transformer.
3. Earthing transformer.
4. 11 kV/33 kV/440 V, 5 000-kVA transformer.
5. Earth leakage transformer.
6. Motor-operated neutral isolating switch.
7. 11-kV sealing-ends.
8. Air-break switches.
9. 33-kV steady insulators.
10. 33-kV tension sets.
11. 33-kV tension sets.
12. Neutral earthing resistance.
13. Potential transformer.
14. Hand-operated link.
15. Motor-operated link.
16. 11 kV/132 kV, 21 000-kVA transformer.
17. 11-kV sealing-ends.
18. 132-kV tension sets.

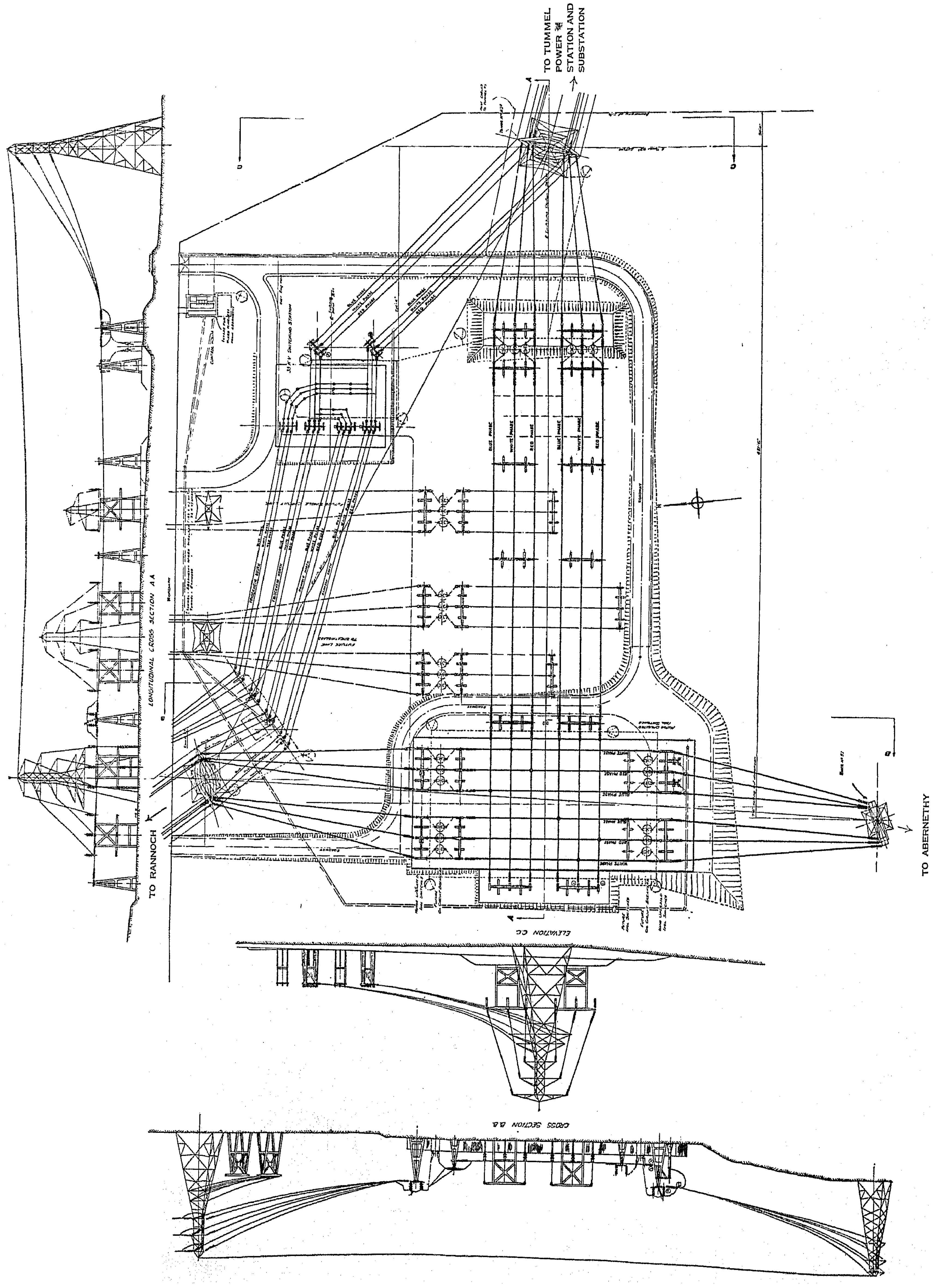

FIG. 13.—General arrangement of Tummel switching station, 132-kV and 33-kV sections.

A control house is provided adjacent to the 33-kV gear, and all connections from this point to the gear and to the power station are made by means of underground cable.

Provision has been made in the lay-out for the installation of future oil switches and also for possible future main transmission lines and their controlling gear, which accounts for the liberal spacing at present.

The whole of the busbars and switches are carried on pre-cast reinforced-concrete frames. This design was decided upon both on the score of low maintenance costs and also on account of the fact that the great spread of the substation did not permit of its being designed satisfactorily as a steel structure. The foundation work was particularly difficult, as there is a layer of peat above the rock, and the uneven nature of the site meant that in some cases the frames had to be carried to excess depths and in others the ground had to be made up.

(*c*) *Abernethy*.—The 132-kV line terminates at Abernethy substation (Figs. 14 and 15), which is equipped with four 20 000-kVA 3-phase transformers of the 3-winding type, star/delta/star-connected, having a nominal ratio of 125/34/132 kV. The 125-kV winding is fully insulated throughout, continuously rated, and provided with taps of ± 8 per cent. It is also suitable for unearthed working at 20 per cent excess normal voltage. The 132-kV winding is designed for direct earthing and for 10 per cent over the normal working voltage. The transformers are air-cooled, naturally up to 60 per cent of full load and by means of air blast thereafter. The input winding has a rating of 20 000 kVA, the 132-kV output winding a rating of 15 000 kVA, and the third winding a rating of 5 000 kVA. This third winding is delta-connected, and is designed with a thermal rating of 12 500 kVA, thus ensuring that each winding of the transformer has an equivalent thermal rating under fault conditions. The air-break switches on the incoming side are used merely for the purpose of disconnecting the transformers. The 132-kV oil switches are on the delivery side and are equipped with the necessary protective gear and control arrangements. There is also a 33-kV switching station on the same site as the 132-kV substation. The plant capacity provides transformers capable of delivering 60 000 kVA to the grid system without being overloaded, and 20 000 kVA to the Grampian local system. It is interesting to note that the supply to the whole of this 33-kV substation is obtained from the third winding of the main transformers, and that there is no direct coupling with the 132-kV system. The incoming 33-kV supply is controlled by automatic-reclosing switches arranged so that the advantage of the duplicate supply of the two 132-kV overhead lines is obtained.

Use is made of the third winding of the transformers for the purpose of metering. There is no 132-kV potential transformer, and the voltage for the metering arrangement, compensated to agree in phase and ratio with the 132-kV voltage under all load conditions, is obtained by means of compensated 33-kV potential transformers. The current for the metering is obtained from current transformers in the neutral of the 132-kV grid system, which is dead-earthed.

The substation structure is steel-framed concrete-clad, similar in design to that at Rannoch.

### *Transmission Lines.*

The main transmission line from Rannoch for a distance of approximately 14·7 miles up to the Tummel power station consists of steel towers of an average height of 97 ft., with extensions to suit the varying ground conditions. These towers carry four separate circuits, two for 132 kV and two for 33 kV, the former lines being arranged at the top and the latter underneath. The construction arrangement is as shown in Fig. 16. The spacing between the several circuits was specially considered with reference to the inductive interference and also with a view to ready maintenance. Each of the four circuits can be safely approached with the other three alive. The normal span is 900 ft., but in some cases this was extended to a maximum of 1 500 ft. The conductor employed is 37/·110-in. steel-cored aluminium, the earth wire being of the same material (19/·110 in.). The insulators are of the Hewlett type with 12 units for each string on the 132-kV circuits and 3 units on the 33-kV circuits. Guard rings and arcing horns are provided throughout, and are specially graded near the substations to afford protection from excess voltages due to surges.

During normal working conditions there is no interference between one circuit and another. Each circuit is transposed, and earthing resistances are provided in the neutral point of each circuit. Under fault conditions there is an unavoidable electromagnetic coupling between the faulty circuit and the healthy circuit, but, as the neutral point of each circuit is independently connected to earth, no appreciable voltage-rise occurs in any one system.

To protect against the remote and unlikely possibility of a 132-kV line coming in contact with a 33-kV line, protective arcing-gaps are provided on the latter. Also, in the event of a 132-kV line breaking whilst this was in a loaded condition, the negative phase-sequence relay protection would operate, owing to the unbalanced load currents. The 132-kV apparatus is protected from damage due to possible abnormal voltage surges by a series of graded arc-gaps fitted on line towers on the incoming sides of all substations.

At Tummel Bridge the four circuits separate. The 33-kV lines, after looping in and out of the switching station, are carried on for a distance of approximately 60 miles, terminating in Friockheim substation a few miles from Arbroath. The 132-kV lines continue in a southerly direction down to Abernethy, where they are connected to the step-down substation; at this point the voltage is reduced for the company's distribution purposes, and a supply is also given to the grid system. The 33-kV line to Friockheim is erected on wood poles of the H type, the 132-kV line being carried on steel towers throughout.

All the steel towers are of galvanized steel on concrete foundations, and are fitted with the usual standard equipment such as earth pipes and anti-climbing guards. The construction of all these lines offered many problems owing to the difficult conditions of the ground, particularly of the high moorland between Tummel and Aber-

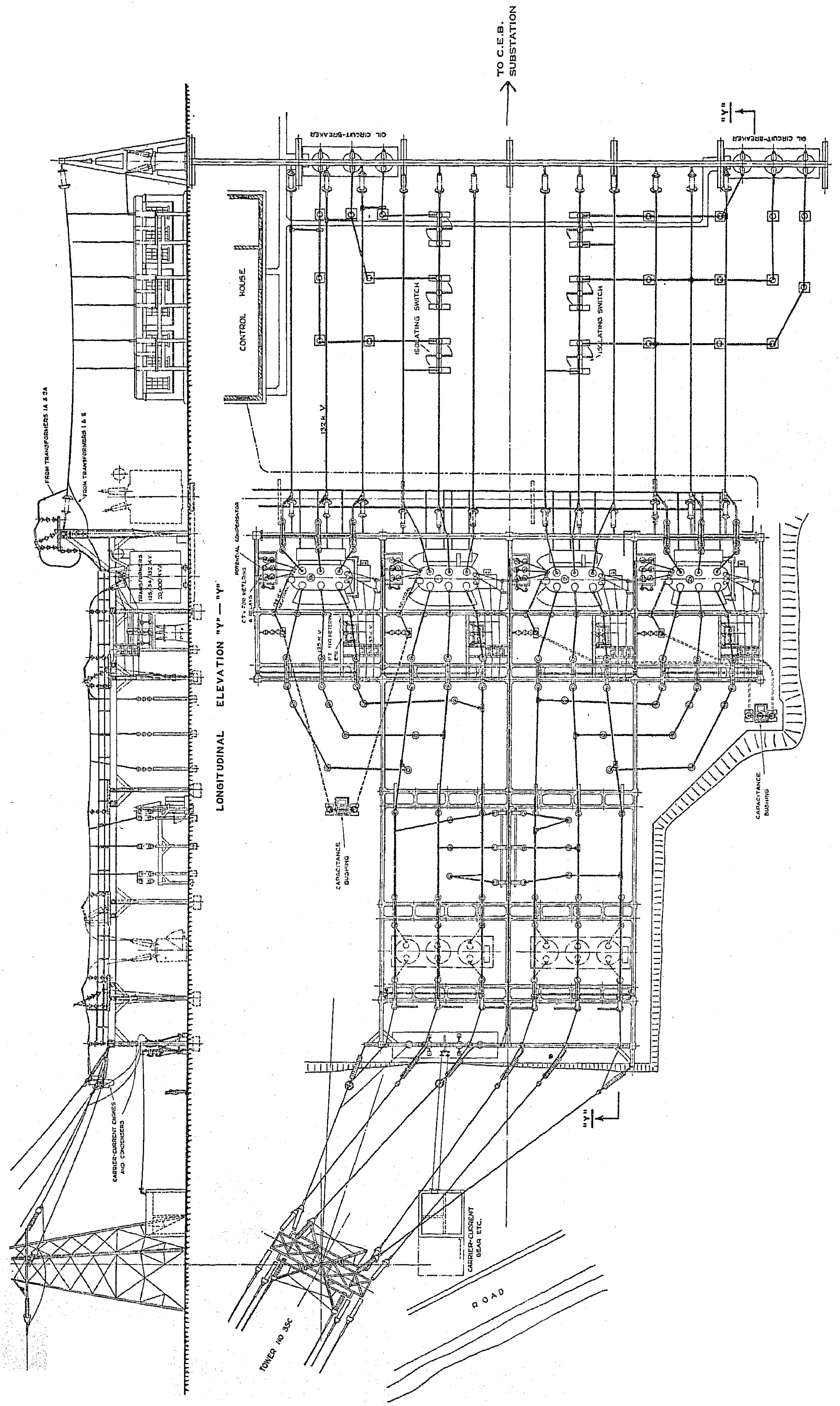

FIG. 14.—Arrangement of 132-kV substation, Abernethy.

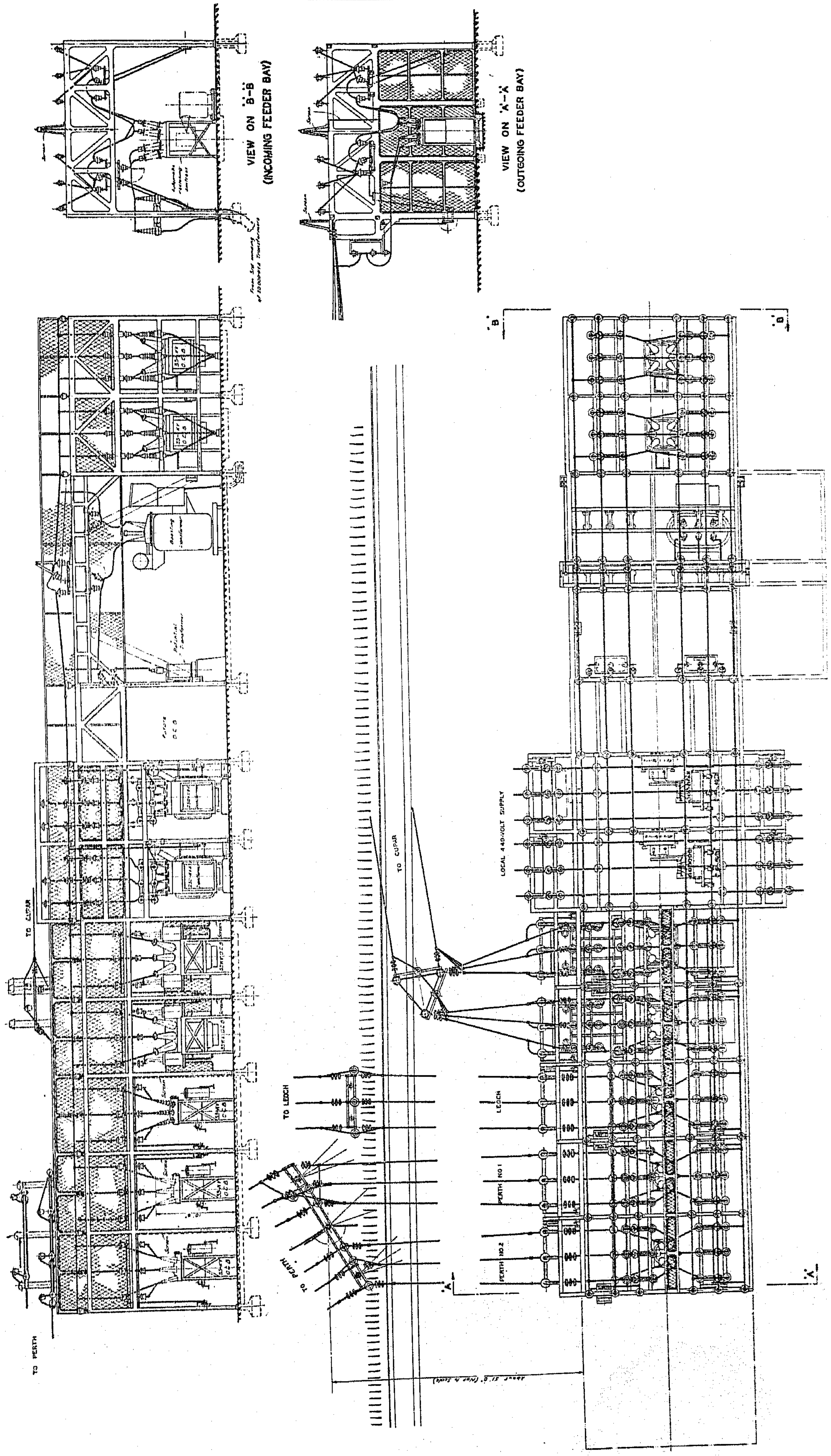

FIG. 15.—General arrangement of 33-kV section of Abernethy substation.

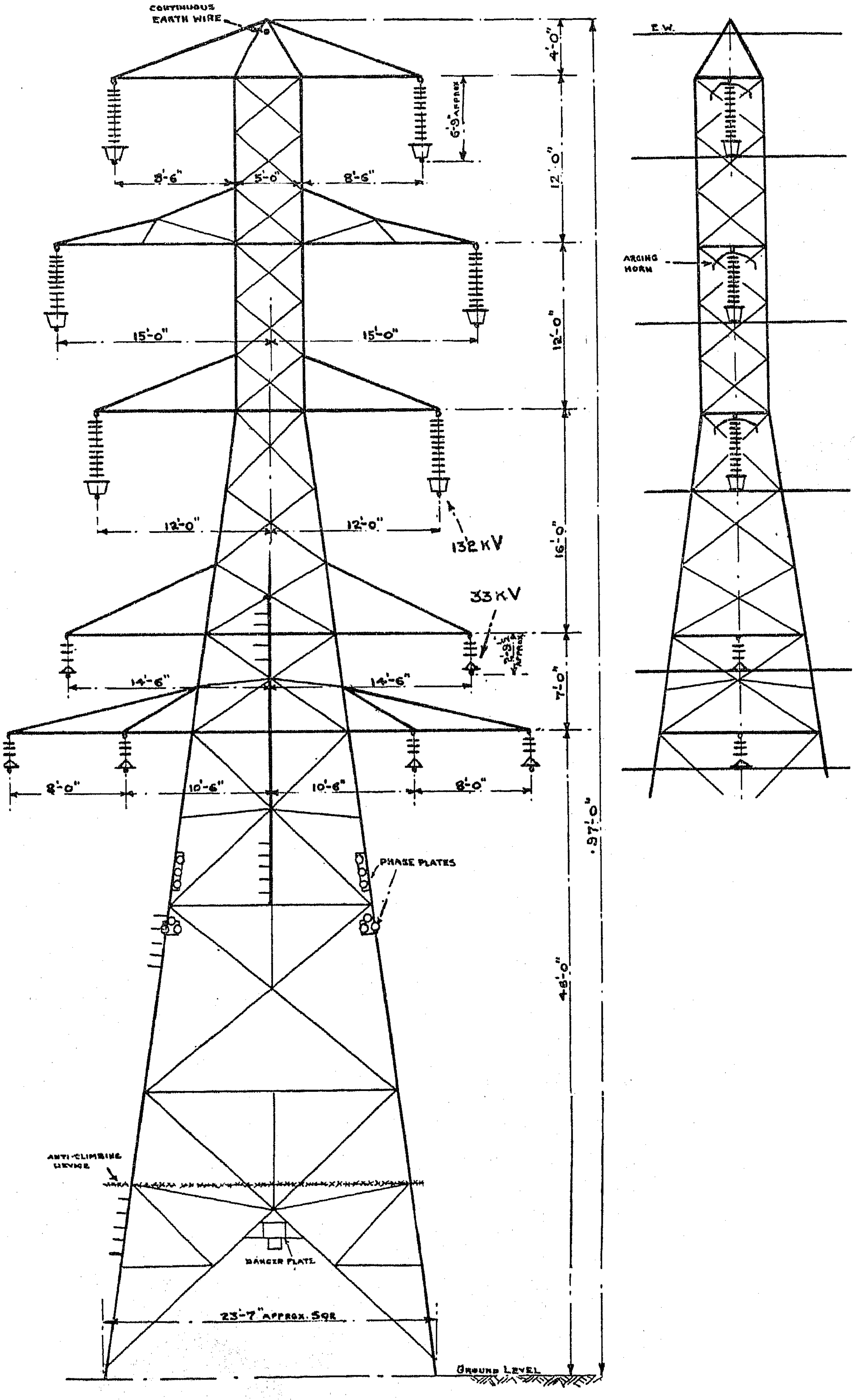

FIG. 16.—132/33-kV transmission tower, "S" type. Rannoch–Tummel.

feldy, and in many cases the material for the transmission line had to be manhandled for considerable distances. Foundations were particularly difficult owing to rock and the slope of the ground, also to the fact that in many cases the towers had to be placed well up hillsides, far from the nearest roadway. Earthing connections were also difficult to obtain and each position had more or less to be dealt with separately, very few foundations being alike.

### *Load Control, Protection, and Communications.*

(*a*) *Load control.*—At the Tummel station, from which the entire power supply of the system will be regulated, the power is controlled from the switchboard gallery (Fig. 7). The main switchgear is all electrically operated from the control board, and the remaining portion of the switchgear for l.t. supplies is mounted in an adjacent position on the gallery, so that it is easily accessible to the operator.

The station, substation, and system arrangements, have been designed so that the whole station and the external switching can be controlled by one operator, who has also complete charge of the machines, which are entirely remote-controlled. On the control desk all the communication arrangements are provided in connection with the whole system, this desk being located in front of the main control board. On the left-hand side is situated a bench with a diagram, indicators, control switches, and recorders for controlling the conditions on the water side. To the right is the remote-control switchboard for the Abernethy substation, which controls the 33-kV lines supplied from that place and also the main connection to the Central Board's lines. From this position the operator is also able to view the main switchboard, which is arranged in an arc of a circle, and mounted on the building stanchions on the left- and right-hand sides of this arc are the alarm indicator panels. Any abnormal occurrence in the station causes an audible alarm and lights an indicator notifying which circuit or which piece of apparatus or plant requires attention. Over each control panel there is a clear indicating label, and if the circuit is alive this label is illuminated.

The 33-kV load can be taken either in whole or in part by Tummel, and will require no special attention since the voltage and control of the system is automatically regulated. The 132-kV load is automatically controlled; this is effected by an automatic load-controller working on either or both machines, which, provided conditions are healthy, enables a predetermined load to be delivered. If an abnormal demand occurs, the controller is tripped out, and the machines are left free to deal with such a condition. Automatic frequency control can also be used as an alternative to load control. The arrangement for cutting out the load controller is actuated by frequency variations, the load control being automatic only when the frequency is maintained within preadjusted limits.

In the event of it being required to run up a new machine, it is only necessary for the operator to turn the starting switch on the turbine control panel. The operation of starting can be followed from Fig. 17, and is as follows. The guide vanes will be in the closed position, and the quadrant will be locked. The oil pressure will have previously been brought up to the required value by means of the auxiliary pump. To start up the turbine, the main switch E is closed. This action puts a solenoid F across the accumulator busbars, through various protective devices, of which the most important is a switch coupled to the main inlet valves, the completion of the circuit only being possible when the valve is fully open. When the solenoid F is energized, it opens a valve which allows oil to pass to the gate lock G. This lock is then operated and the quadrant H released. The movement of the lock automatically opens a port through which oil is delivered to the main governor regulating valve I, and thence to the servo motor, which then opens the guide vanes by pushing down the quadrant H. In the meantime the brake on the turbine shaft has been released, so that the turbine starts up.

Arrangements are also made so that automatic synchronizing gear can be added later; it will probably operate as follows. When the turbine has reached a speed of approximately 95 per cent of the normal value, the secondary starting switch J is closed. It will be observed that this brings a hunting relay K into action, and this relay, which operates the speed-adjusting solenoid L, at once assumes control and allows the speed of the turbine to rise slowly to its normal value. Should the unit not be in phase with the line, this relay allows the speed to rise to about 5 per cent above normal. At this point the 2-way switch is thrown over, reversing the current through the relay and causing the solenoid L to act in the opposite direction. The speed then begins to drop slowly, and if the phasing is still incorrect when the turbine is passing through normal speed the hunting action continues until synchronizing can be effected either by hand or automatically. As soon as the machine is synchronized, the relay is cut out and the governor assumes control of the turbine. The attendant can still control the turbine through the switches N, which are of the push-button type mounted on the switchboard. To prevent the load on the turbine exceeding a predetermined value, a load-limiting stop P is fitted.

The sequence of operations for shutting down the machine is somewhat similar to that employed in starting up. After the main circuit breaker has been tripped, the switches E and J are opened, with the result that the servo motor closes the vanes, which are then locked. The speed then begins to fall, and when a speed of 150 r.p.m. is reached the under-speed pendulum contacts open, de-energizing the solenoid on the brake valve and allowing the brake to come into action.

The indicating instruments on the turbine control panel show whether all the automatic electrically-controlled circuits are in healthy condition, and they also provide for any emergency, so that in the event of a failure or of the machine running away everything is automatically taken care of.

A device is provided whereby, in the event of the governor belt breaking, the turbine is held so that it can deliver a fixed load equal to that which was on the machine at the time of the belt breaking. An alarm is, however, given, and the second machine can be immediately run up and the first machine shut down for attention. The load on the machine can also be limited at any time so that it will not deliver more than a predetermined value, and the limit of this load can be adjusted from the switchboard.

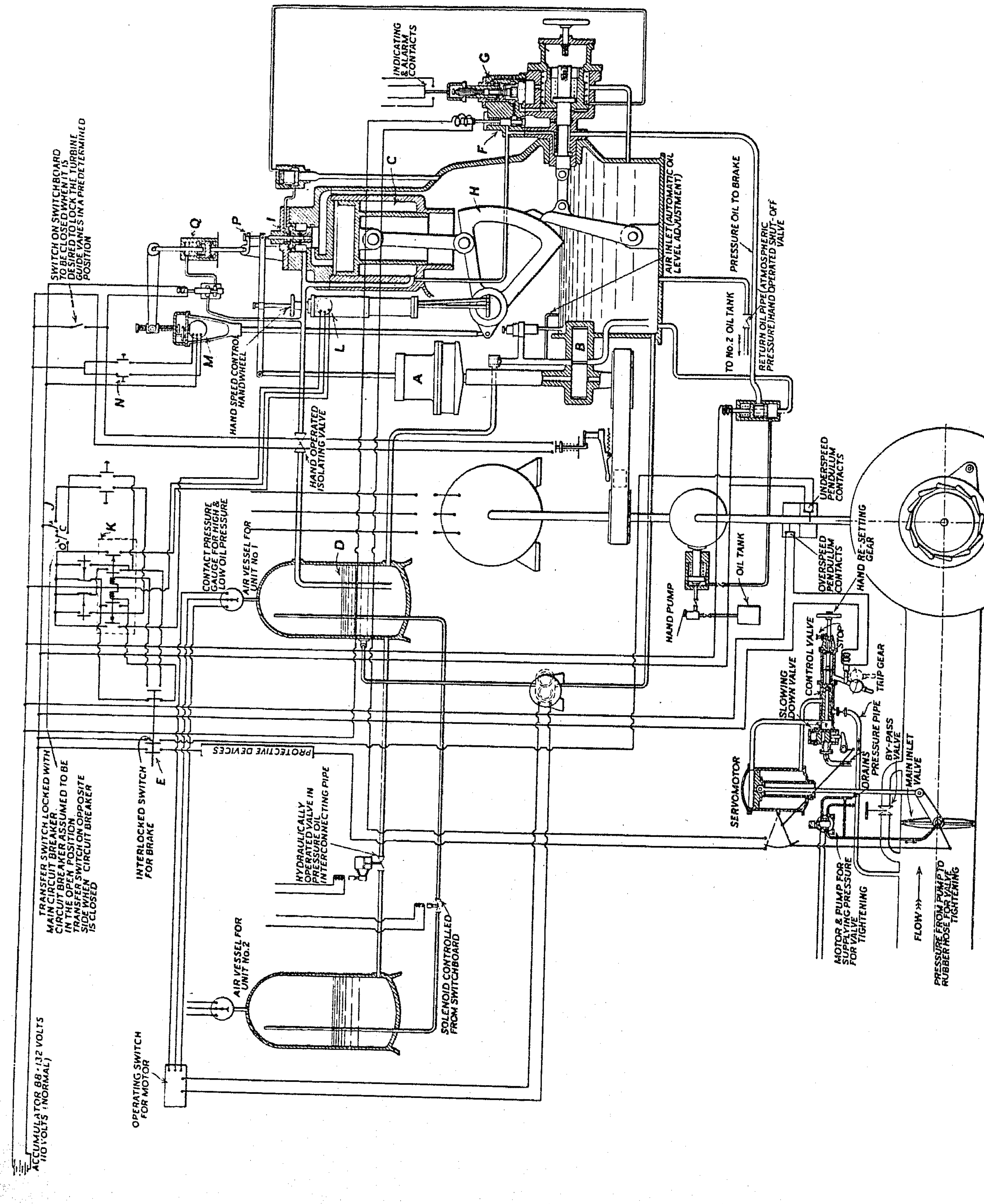
INDICATING & ALARM CONTACTS
G
F
C
H
SWITCH ON SWITCHBOARD TO BE CLOSED WHEN IT IS DESIRED TO LOCK THE TURBINE GUIDE VANES IN A PREDETERMINED POSITION
Q
P
I
S
M
N
L
A
B
HAND SPEED CONTROL HANDWHEEL
HAND OPERATED ISOLATING VALVE
AIR INLET (AUTOMATIC OIL LEVEL ADJUSTMENT)
PRESSURE OIL TO BRAKE
TO No.2 OIL TANK
RETURN OIL PIPE (ATMOSPHERIC PRESSURE) HAND OPERATED SHUT-OFF VALVE
UNDERSPEED PENDULUM CONTACTS
OVERSPEED PENDULUM CONTACTS
HAND RE-SETTING GEAR
J
K
CONTACT PRESSURE GAUGE FOR HIGH & LOW OIL PRESSURE
AIR VESSEL FOR UNIT No 1
D
OIL TANK
HAND PUMP
CONTROL VALVE
STOP
TRIP GEAR
SLOWING DOWN VALVE
PRESSURE PIPE
BY-PASS VALVE
DRAINS
MAIN INLET VALVE
SERVOMOTOR
PROTECTIVE DEVICES
E
TRANSFER SWITCH LOCKED WITH MAIN CIRCUIT BREAKER. CIRCUIT BREAKER ASSUMED TO BE IN THE OPEN POSITION TRANSFER SWITCH ON OPPOSITE SIDE WHEN CIRCUIT BREAKER IS CLOSED
INTERLOCKED SWITCH FOR BRAKE
HYDRAULICALLY OPERATED VALVE IN PRESSURE OIL INTERCONNECTING PIPE
MOTOR & PUMP FOR SUPPLYING PRESSURE FOR VALVE TIGHTENING
FLOW
PRESSURE FROM PUMP TO RUBBER HOSE FOR VALVE TIGHTENING
SOLENOID CONTROLLED FROM SWITCHBOARD
AIR VESSEL FOR UNIT No.2
OPERATING SWITCH FOR MOTOR
ACCUMULATOR BB-132 VOLTS 110 VOLTS (NORMAL)

FIG. 17.—Diagrammatic lay-out of automatic control for turbines at Tummel.

(*b*) *Rannoch load indication.*—The indication of Rannoch load is obtained on the control board from current transformers located in the lines on the incoming side of the Tummel switching station. The voltage of the 132-kV supply, and the power factor, are obtained from 11-kV potential transformers compensated to agree with the supply voltage. The 33-kV supply is obtained direct from potential transformers.

(*c*) *Control of air-break switches.*—Arrangements are also provided on the control board so that the 132-kV and 33-kV tie lines between Rannoch and Tummel

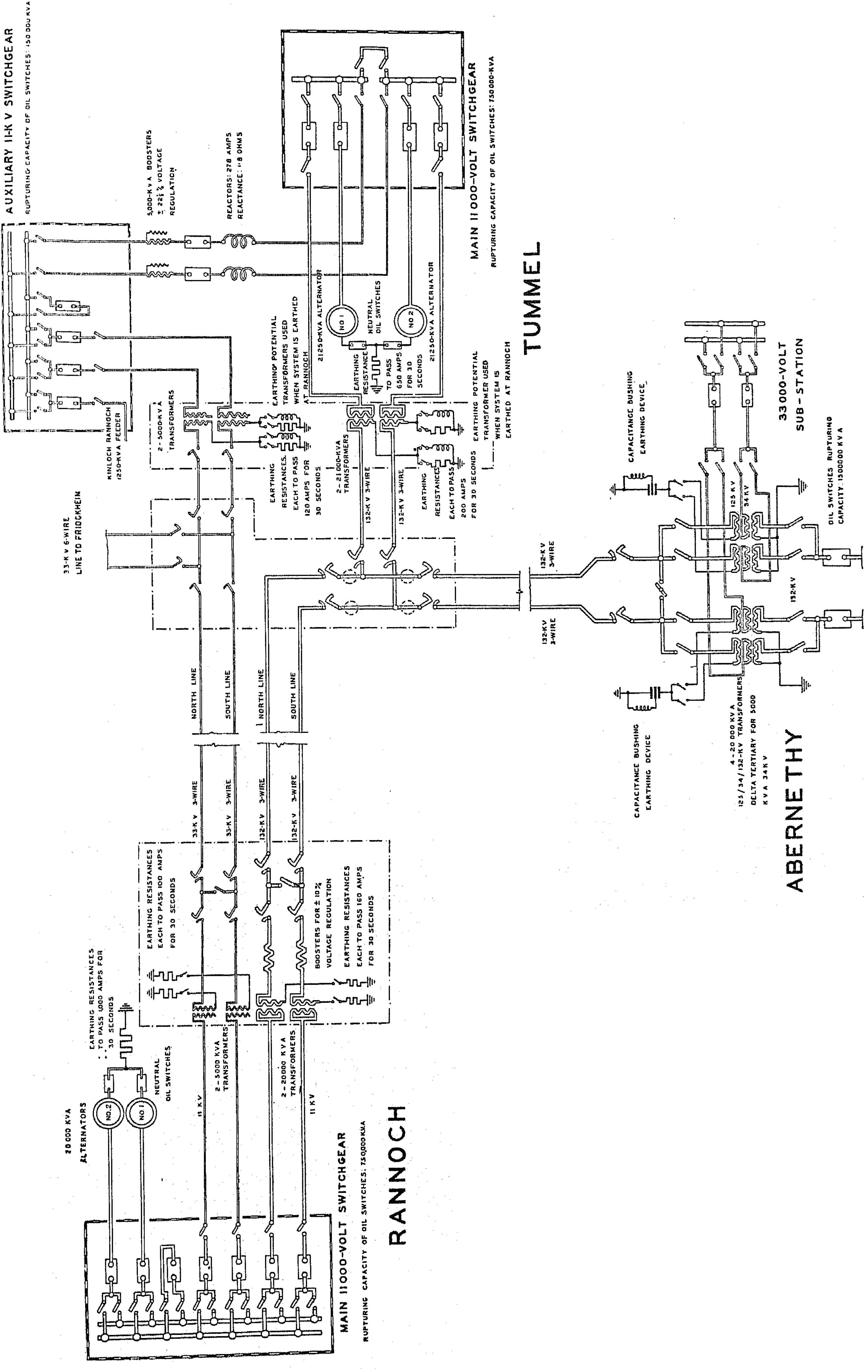

FIG. 18.—Diagram showing method of protection.

can be broken. For this purpose, motor-operated air-break switches are provided in the switching station. These are remote-controlled and interlocked so that they cannot be opened unless the current flowing is reduced to negligible proportions.

Similar switches are provided for breaking the magnetizing current of the 132-kV and 33-kV transformers. These are interlocked with the transformer main supply switches so that they cannot be operated under load.

(*d*) *Control of neutral resistances.*—To facilitate the changing of the neutral earthing arrangements, remote-controlled air-break switches are also used. Each 132-kV and 33-kV line is normally earthed through its own earthing resistance at Rannoch, and at Tummel; the transformer neutrals are earthed through potential transformers; but if the Rannoch earth is removed a resistance earth can be added by operating the motor-controlled air-break switch from the main control board.

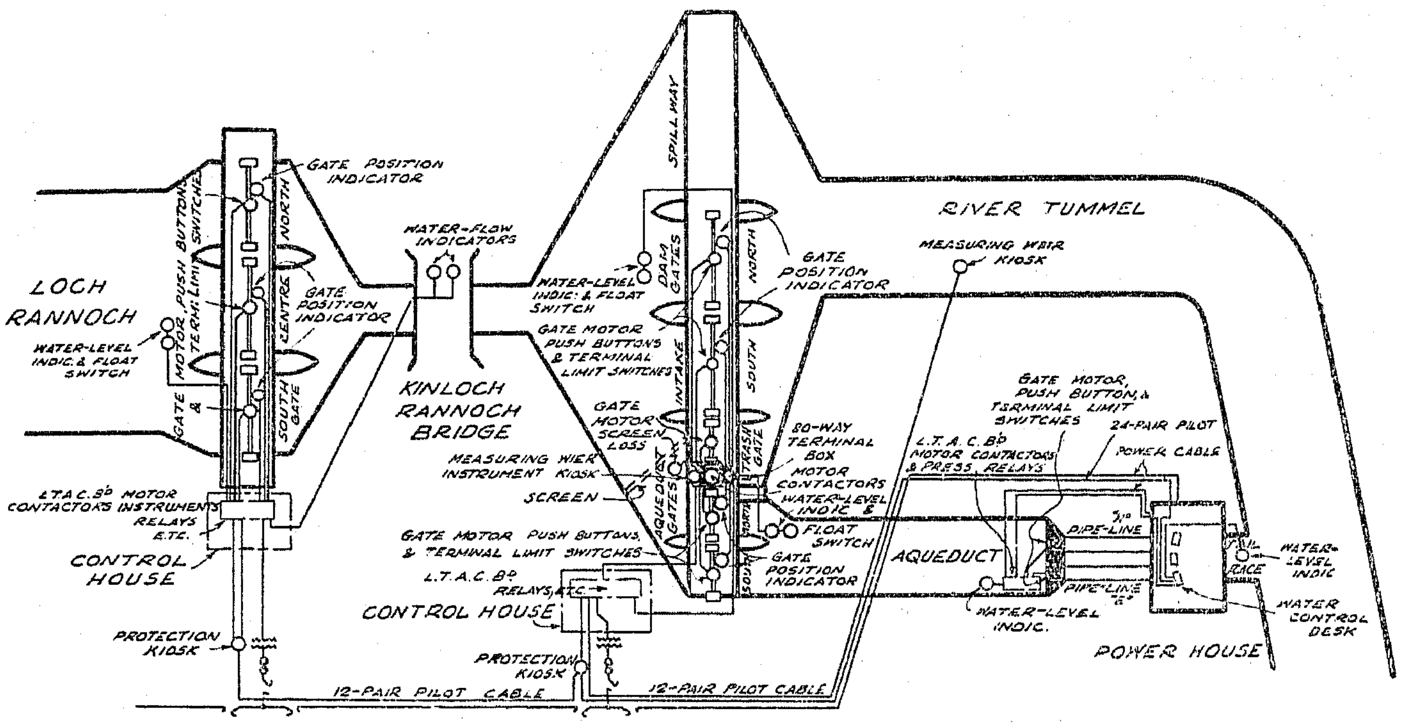

Fig. 19.—Water control diagram.

(*e*) *Protective arrangements.*—For protecting the machines, local feeders, and general plant, the ordinary standard and up-to-date practice is adopted. For protecting the main lines and main transformers the arrangements are as shown in Fig. 18. Each main line with its step-up and step-down transformers is regarded as one unit for both switching and protective purposes. The earth-fault current is limited by a resistance, so that the effect of any earth fault is reduced in severity. Earthing is effected at one point only, and each separate unit has its own earth connection.

The protection is designed to clear the whole faulty unit, and leave the other duplicate unit in commission.

For phase-to-phase faults, inverse time relays are used in combination with directional overcurrent relays, with negative phase-sequence relays as stand-by protection.

(*f*) *Water control panel.*—The water control panel is of the desk type, and is arranged as shown in Fig. 19. The background indicates the general lay-out of the water flow, and indicating instruments are located in diagrammatically correct positions. From these instruments the amount of each water-gate opening and also the rate at which water is flowing into the main channel can be seen. The rate of compensation water flow is also indicated.

The switches underneath each gate-position indicator can be used for the remote control of the gates, so that the water may be varied to suit the operating conditions.

Indicating lamps show whether the water is rising or falling, and the indicating instruments associated with these give the actual level of the water at each important point. Any failure in the local supply is automatically indicated, and an alarm given.

On the front vertical portion of the desk, graphic-type recording indicators are housed.

Under certain extreme water conditions the operation of the gates has to be carried out with great precision, and accordingly automatic arrangements are provided on the site so that when these conditions arise the control is taken over automatically, and the gates then operate to suit the abnormal water conditions. This control cannot be interfered with, either at the power station or on site. Also the water flow in the aqueduct can be automatically balanced against the load without any manual control. The scheme therefore provides a self-controlled arrangement which can be adjusted by hand within safe limits.

It may also be mentioned that when any gate is functioning automatically the position and operation of the gate can be seen from the control panel, and thus a check can be kept upon the automatic working.

(*g*) *Telephonic communication.*—Telephonic communication is provided by pilot cable from Tummel to the switching station and also to the control weir and intake dam, so that if necessary the hand control of the water gates can be directed from the power station.

A feature of additional interest is the arrangement of communications between Abernethy and Rannoch. The speech frequency from an ordinary telephone is amplified and connected to the grid of a transmitting valve which controls a wireless transmission circuit,

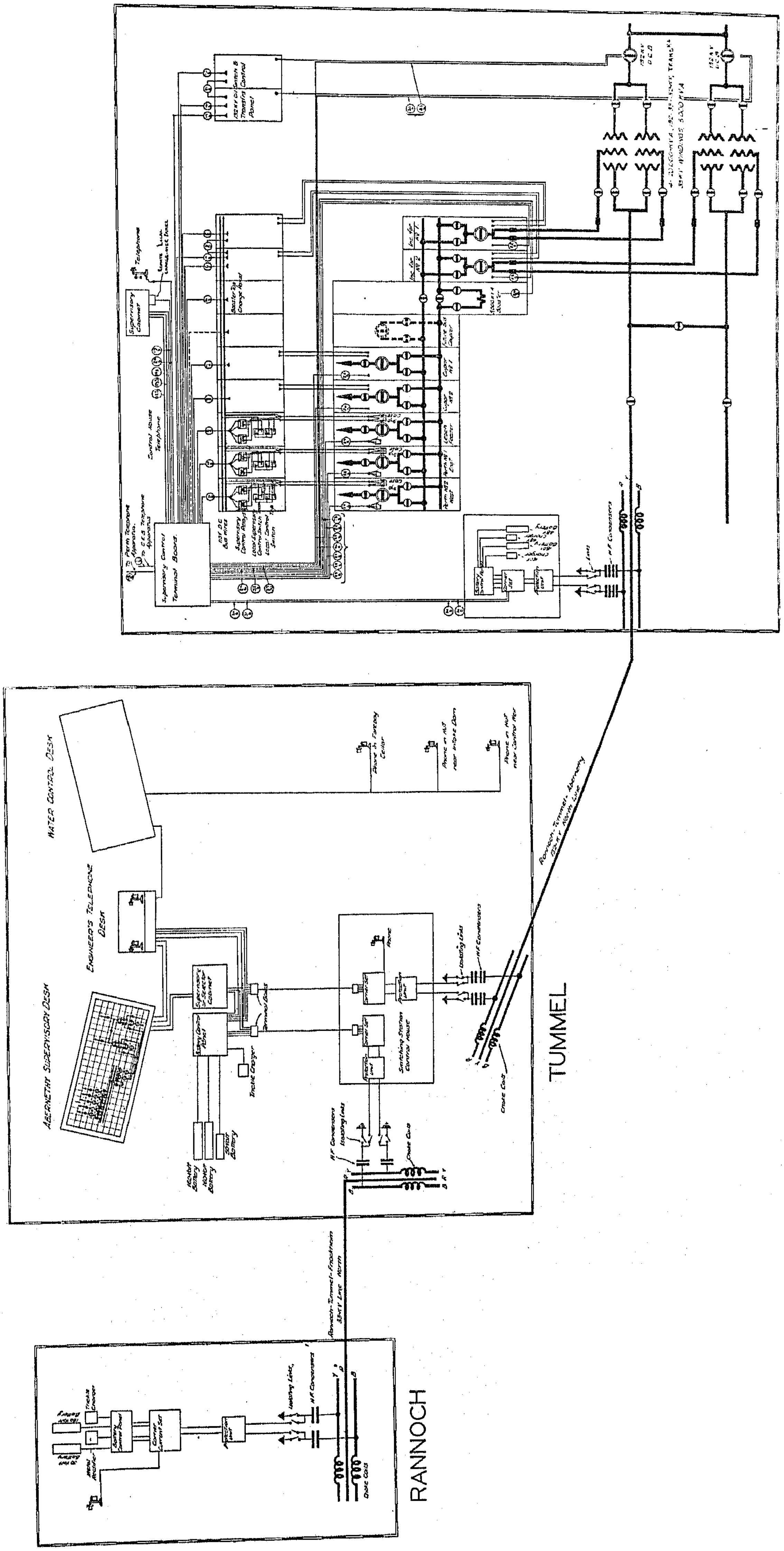
ABERNETHY
TUMMEL
RANNOCH
WATER CONTROL DESK
ENGINEER'S TELEPHONE DESK
ABERNETHY SUPERVISORY DESK
Supervisory Control Terminal Board
Control House Telephone
Choke Coils
R.F. Condensers
Loading Coils
Rannoch-Tummel-Abernethy 132 K.V. Line
Rannoch-Tummel-Pitlochrie 33 K.V. Line

FIG. 20.—Diagram of connections for high-frequency telephony and supervisory control, Rannoch–Tummel–Abernethy.

and in this way the voice frequency is superimposed upon a wireless frequency as is done at a broadcasting station. The carrier wave, i.e. the wireless wave, is modulated by the voice, and the high-frequency current is passed through a pair of condensers to the 132-kV overhead line. At the other end of the line it is tapped off through condensers into a receiving set in which demodulation takes place, the equipment being, in effect, similar to a wireless receiver. As the high-frequency current has a frequency of over 1 000 times that of the 50-cycle supply there is no difficulty in separating the power transmission from the carrier current. The frequency of transmission on the 132-kV section is approximately 130 500 cycles per sec., and that of the calling wave is approximately 81 000 cycles per sec. This arrangement has been working between Rannoch and Abernethy very satisfactorily since the starting-up of the Rannoch station over 3 years ago. It has now been extended so as to enable communication to be obtained over Post Office landlines with the Central Board's central office at Glasgow. It has also been extended to the Grampian Electricity Supply Co.'s station at Perth, and Tummel has become the centre of the whole system. The telephone control is placed on the desk mentioned above, and any of the points may intercommunicate, i.e. Rannoch, Tummel, Abernethy, Perth, or the C.E.B. office.

(*h*) *Supervisory control.*—The system has been extended to provide for remote control of the Abernethy switchgear. By this means the Grampian Co.'s oil switches there can be opened or closed, and the current and voltage in each circuit indicated. A mimic diagram is provided on the supervisory panel, the indicating instruments and operating keys being part of it. Tummel can at any moment exercise priority over any operation that may be in progress. The scheme is also capable of extension to Rannoch, as regards both switching control and, to a limited extent, the operation of the machines themselves.

The supervisory control referred to above uses the same channel for transmission as the main carrier-current communication, and supervisory operations may take place while speech is in progress. The main features of the scheme are shown in Fig. 20. The indicators and operating keys necessary for the various operations are mounted on the control desk, and if any failure occurs or any adjustment is required an alarm is given.

## DISCUSSION BEFORE THE INSTITUTION, 8TH NOVEMBER, 1934.

**Prof. W. M. Thornton:** Those of us who have visited the fine engineering feat which has been described must be glad to see that a permanent record has been made of it in this paper. Most of its visitors have seen it under favourable summer conditions, but I have been told by engineers who have carried out the work up there that the conditions during the winter are not by any means so favourable! The authors mention Avonmouth. I do not know whether they are familiar with the district, but there is on the River Avon between Bristol and Avonmouth a little station called Sea Mills. I lived in the neighbourhood for some years. There was a tidal basin there, and the tide of the river, which was 40 ft. or more, used to fill up this basin, which was emptied during the ebb of the river, driving a mill. That device had been used, it was said, since Roman times, so that the utilization of tidal power is not exactly new. Those of us who have had the pleasure of seeing some of the great water-power schemes in the United States, Canada, New Zealand, and elsewhere, have often wondered when our own potentialities in that direction would be fully utilized. I think we are coming within reach of that; there remains the great Severn tidal scheme, though I think it will be a long time before that matures.

**Mr. W. E. Highfield:** Under the heading "The present situation in Great Britain," the authors state that "it must be demonstrated that hydro-electric power in any given instance can produce power at any rate as cheaply as an alternative supply from coal on the same site." Is it correct to attach that little rider, "on the same site"? I think it is not; for of what use is electricity on the site to anybody? Electricity, like any other commodity, can be used only when it is actually delivered to where it is to be consumed. I hold that the rider should read: "to supply the same load." If a power scheme is under consideration, and it is a question of whether a steam or a water-power station should be used for supplying the load, then quite naturally the engineer will choose the most favourable position for each. For the steam station he will choose the most suitable position for the reception of the raw material and the delivery of the finished product to the load centre, and there he has greater flexibility than he has in the case of the water-power station, which is tied fairly closely to its natural site. I know of only one instance in which where there has been a change in motive power the new prime mover has been put on the same site as the old, and that was in the tin-mine industry in the Tamar Valley, around Kit Hill. The original prime movers in that case were windmills, and they were naturally placed on the tops of the hills and connected by very long shafting to the pumps farther down the hill. When the steam engine ousted the windmill, the engineers, rather than face the difficulty of moving all this shafting, put the engines on the tops of the hills, and all the coal has to be carried up there to them. That is probably a unique case, and I do not suggest it should be copied by anyone! Going somewhat further into the question of the delivery of the raw material, British water-power schemes are notably different from those on the Continent in one respect. On the Continent nearly all the schemes draw their raw material, their water, from the snow-line on the high mountains. This snow storage costs nothing, and, although the material is not available until it has been heat-treated by the summer sun, nevertheless it does ensure a constancy of supply. In England, on the other hand, that does not hold good; here we have wet and dry seasons, and we have had notable instances of the dry seasons quite recently. The cost of storage thus becomes a determining factor. On the question of the delivery of the electricity to the load centre, a profound change has come over the situation owing to the advent of the national grid. So widespread are these national grid lines that the site of any new projected scheme of generation is almost always nearer to a grid point than it is to a load centre. The grid line carries 50 000 kVA in each direction, so that a grid connection is worth 100 000 kVA. I am, of course, giving somewhat general figures, and circumstances may alter them; but they are perfectly sufficient for the purposes of this discussion. The fact remains that these transmission lines exist; they have been paid for, and they are there to be used in the public interest. They will affect water-power schemes very considerably, and, in a less degree, steam schemes also, because they will shorten very considerably the distance to the load centre. I think it is not out of place to remark here that transport is a much more important part of commerce than production. Production can quite readily be increased, and there have been recent instances where production has been increased too much, but to increase transport is a problem which is continually taxing our ingenuity. The grid is the largest national contribution to the increase in the transport of electric supply which has been carried out.

It is made very clear in the paper that there are two main uses for the water power which we have available in this country, the one being for public purposes and the other for specialized commercial undertakings. These commercial undertakings are so specialized that they can only use water power; steam-produced power is too dear, and even the water power must be favourably arranged; that is to say, it must have a short delivery for its raw material, and on the delivery end there must be no transmission. Although it is not stated in the paper, I believe it is a fact that even conversion from alternating current to direct current would considerably add to the cost of the product. We have so little water power in this country that it may be worth considering whether some of it should not be specially earmarked for commercial development. When we consider the great aluminium industry, and all the capital and labour that it employs—labour employed not only in the production of the metal but also in all the multifarious uses to which aluminium is put—it is, I think, an arresting fact that the units of electricity generated at those works are of infinitely more value to the general public than if they had been distributed in the form of electrical energy for ordinary uses. Much might be said on the subject of the effect of existing water-power schemes on fishing, both net and rod, on the meadow land through which the controlled rivers and steams flow, and on other agricultural matters. Much will be said on these matters either here or elsewhere, and I think much ought to be said; because if there is one way in which the engineer is sometimes a little lacking it is that he does not always consider that if damage is done in these directions that damage is irreparable.

**Mr. W. T. Halcrow:** It is just 30 years since I first became interested in hydro-electric work. On that occasion I paid a visit to Spain. Very shortly after that I became engaged as assistant engineer on the design and construction of the Kinlochleven works, which are briefly referred to by the authors. Turning to the paper, I do not propose to say anything about the development of water power in England and Wales. There is no very great quantity. Reference has already been made to the Severn tidal power schemes and in my opinion the report which was recently issued has indefinitely postponed any development of that work. So far as water power in Great Britain is concerned, interest centres in Scotland. The authors refer to the estimated total of power which was given in the report of the Water Power Resources Committee, the figure for Scotland being roughly 200 000 kW of continuous power. My own investigations lead me to believe that the potential power is at least 320 000 kW, and possibly more. Of that 320 000 kW, some 160 000 kW have already been developed, or the works for developing that power are nearing completion. The authors state that there still remains scope for considerable development in certain districts, and with that remark I entirely agree. It is said in some quarters that the schemes yet to be developed in the Highlands of Scotland are too isolated to be of much practical value, but I do not think that that is correct; there are several excellent schemes which are situated within a comparatively short distance of the sea and of railway facilities, and, moreover, it would not be unreasonable to expect that industries requiring a large quantity of electrical power might follow the example of the British Aluminium Co., and establish factories in the Highlands of Scotland. Much has been said and written in the past, and much more will be said and written in the future, on the relative cost of power developed from steam or water; but the fact that the British Aluminium Co., in extracting the aluminium from its natural ore, carry out one process in Fifeshire on the coalfield and then take the partly-prepared product to the Highlands of Scotland for the sole purpose of obtaining the cheapest power they can get, is surely an argument that there is nothing cheaper in this country than power from water in those circumstances. Mr. Highfield touched on the question of the relative cost of power derived from water or from coal. My own view is that if one takes the power as delivered, as he would have it, at a definite point, and the estimated cost at that point is the same in each case, then taking a long view the balance will be in favour of water power. The capital cost of the undertaking will naturally be written down by means of an annual sinking fund, and in the end the cost of the power will be made up of small capital charges only—whatever is left—and very small running costs, the actual source of power being the rainfall, which costs nothing. The same cannot be said of a steam station, because fuel will always have to be purchased, whatever the period, and, moreover, the machinery will require frequent renewal over a period of 70 or 80 years. I have often heard it said that there is much greater scope for increasing the efficiency of steam plant than there is for increasing that of water-power plant, because in the former case the value of the heat power obtained is about 25 per cent, whereas with water power one can attain a figure of about 80 per cent. I do not think it is necessary to go very far into that, however, because the argument does not warrant close investigation. Reverting to the paper, the authors have described a variety of developments in Scotland, and I should like to draw attention to the three main types of water-power development in that country. First of all, we have the type which derives its power from water drawn from a catchment area and collected in reservoirs which have a capacity sufficient to regulate completely the water flowing from that catchment area; that is to say, even in dry years such as this the capacity of the reservoirs is such that one can always rely on deriving the average yield from the catchment area. Coupled with that, this first type has a power station which works on approximately 100 per cent load factor. Examples of this type are the Kinlochleven and Lochaber power stations of the British Aluminium Co. For the second type I assume the same conditions for the reservoir storage capacity, but the power station is working on a lower load factor, and in this type I include the Grampian scheme, where the load factor may be of the order of 50 per cent. The third type comprises those schemes which derive their water from rivers and other sources where the supply is only partially regulated, and in this class we have the Clyde Valley Power Co.'s stations at Bonnington and Stonebyres. They derive the water from the river, and there is no storage there at all; but they are extremely useful stations and must be of great value to the Clyde Valley Co. Another scheme is the large development now being carried on in Galloway, where for physical reasons it is not possible to regulate completely the water available; in this scheme there are a number of stations which will work on a load factor of the order of 20 per cent. It follows from this that the high-load-factor schemes are the cheapest to construct, because all the aqueducts are of minimum size, and they form a large part of the capital cost. The moment the load factor is reduced, say, to 50 per cent, the size of the aqueducts, pipe-lines, and power plant, must be doubled to take up the higher load. There is one matter which it may not be inappropriate to mention at this meeting as it is at present receiving attention in various quarters; I refer to the proposal to organize an inland water survey for Great Britain. Such a survey has been talked about time and again during the last 50 or 60 years. Two years ago, the British Association appointed a committee to look into this matter, and later they were joined by a committee of the Institution of Civil Engineers. It is hoped that, arising out of the efforts of these committees, the Government may be moved to establish this inland water survey. It is of great importance, first of all, to hydro-electric engineers. The basic power in the great schemes described in the paper is water, and the whole of the schemes are based on calculations of the available quantity of water, which is measured by rain gauges. So far as Scotland is concerned, these have been very few and far between. In the case of the Kinlochleven plant, which my firm installed 30 years ago, there were no rain gauges at all on the catchment area when those works were designed, and a map had to be computed showing what the probable rainfall would be over that area. Calculations based on actual rainfall data have to be applied to catchment areas, and then there are the losses from absorption, evaporation, etc., all of which introduce an element of uncertainty. I have referred to the benefit which the survey would be to the hydro-electric engineer, but it would also be of great interest to the designer of steam stations. Unless some other method of cooling is adopted, it would seem that the minimum flow of any river would determine the maximum size of any power station which might be built on its banks. There are two small matters which occurred to me when reading the paper to which it may be of interest to draw attention. The first is the introduction of electric welding in the construction of the Lochaber pipe-line. Not only did we make the circumferential joints of the pipes *in situ*, but we also devised a cast-steel flange for these very large pipes which was electrically welded to the mild-steel shell of the pipes themselves. The electric welding process was also adopted for the Grampian pipe-line. It has been in use on the Lochaber pipe-line for 5 years now, and we have found it entirely satisfactory. With regard to the Tummel aqueduct, the long canal which leads from the intake at Dunalastair, it may be of interest to mention that quite an intricate calculation was necessary to arrive at the height of the wave which would be formed owing to the shutting-down of the power station. It was found that the height of the wave which would be formed on sudden reduction of the total load in the power house would be between 3 and 4 ft., and that it would travel the whole length of the aqueduct (3 miles) in 20 minutes, and then travel back again, and so surge to and fro until the frictional resistance damped it out altogether.

**Mr. J. Williamson:** I have had the privilege of being connected with the Galloway water-power scheme from its inception. When the first investigation was made there was no very definite possibility of an outlet for the power, and it was only after the grid scheme came into being that it was realized that there might be an opportunity of making use of what was evidently quite a large source of power in the south-west uplands of Scotland. It was not at first realized, though it is now quite clear, that such a scheme, developed for supplying peak load, can in suitable circumstances be very much more advantageous than a scheme for continuous load. I think this statement rather contradicts the views expressed in the paper and also by Mr. Halcrow. For example, in the case of one particular power station of a section of the scheme the actual cost of the development per kW is about £28. If it is desired to expand that, so as to have a bigger installation at a slightly lower load factor, the cost of extension is only £11 per additional kW, a figure below anything that can be attained, as far as I know, with steam power at the present time. On that basis it becomes quite obvious that there is a field for the development of water-power stations to take quite low load factors. Another point is that where there is storage and the conditions are such as they are in Western Scotland, and particularly South-West Scotland, we get the water just at the time when we want it. The run-off in the winter time is on the average at least twice as much as in the summer. The winter is the time when owing to large seasonal increase of load on the general grid system in Northern England and Mid-Scotland the water power can be most efficiently employed in taking the peaks of the system load, thereby improving the load factor on the steam portion of the system. Moreover, when one is dealing essentially with peak load it is important to notice that Monday, Tuesday, Wednesday, Thursday, Friday, and Saturday forenoon, are the heavy periods of industrial load; on Saturday afternoon industry slacks off, and on Sunday there is not much doing, so that one can store the water over the week-end. The water can also be stored at night. A 20 per cent load factor, taking these factors into account, does not mean one-fifth of 24 hours a day; it means that during the winter one can take up to 8 hours a day of industrial load, and that is the essential feature of the Galloway scheme, for which it has been designed. Mr. Highfield referred to the advantage on the Continent of having the storage in the form of glaciers or of snow; but, as I see it, that is the greatest disadvantage possible. I am familiar with a good many of the water-power stations in Switzerland and in the Alpine districts of France. Take, for example, the case of the Barberine development which supplies power to the Swiss railways. The Barberine station has a reservoir away up in the hills above 6 000 ft. It is used principally to store the whole of the year's water collected in the summer and transfer it to the winter, for use then when the catchment area is frozen up. That means that the reservoir has to have one year's capacity, whereas in Scotland something like 3 months' capacity is sufficient for equalization purposes. Again, the advantage of high head is to some extent illusory. The period during which one can carry out constructional work at 6 000 ft. in Europe is generally limited to about 100 days in the summer; the work has to be shut down altogether in the winter. So far as the development of power for peak load is concerned, where there is a greater water supply in winter than in summer it is obvious that less storage capacity will be required than if one has to distribute the flow evenly throughout the year. In Scotland one gets a high general flow in the winter and a low general flow in the summer. If a constant discharge of water and a constant output of power are required it is necessary to have reservoirs big enough to store a large quantity of water in the winter and carry it over for use in the summer. To utilize the water to the best advantage on peak load where the demand in the winter is high, the essential point is to spread the winter flow suitably over the winter time, and to spread the summer flow separately at a much lower scale of discharge. I think Mr. Halcrow mentioned that in the Galloway scheme there is in his opinion insufficient storage. No doubt what was in his mind was that there might be deficiency of storage to give continuous uniform power throughout the year. Actually there is ample storage for dealing with peak-load power in the scheme as designed. To some extent there is at times surplus power, because in the areas which are not furnished with reservoirs there is the fluctuation of low water and flood water; but on the other hand all the seasonal reservoirs on the Galloway scheme catch the water from the highest and wettest areas of the hills. We do collect in the reservoirs a very large proportion indeed of the water, and it is sufficient to regulate the supply for the purposes of the peak-load scheme. It should be pointed out, in this connection, that it is not storage of water with which we are concerned but storage of units of power. In that respect the value of a reservoir is not in proportion to its capacity but in proportion to its capacity multiplied by the total head which can be developed as the water passes down through one or more power stations. A cubic foot of water in one reservoir, therefore, may have a very different storage value as regards power from a cubic foot in another. The problem of finding the best arrangement becomes a little more complicated on that account. One of the main recommendations of the report of the Water Power Resources Committee was that in any particular area the development should be such as to make the fullest possible use of the power resources. An endeavour was made to do that in Galloway, and, as a result of very many separate investigations and the trial of different methods of development, the scheme ultimately adopted was arrived at. I think it does make very full use of the resources in that particular area. The report of the Water Power Resources Committee does not mention any scheme investigated for that area, apart from a reference to the possible use as a reservoir of Loch Ken. That loch has been so used on a very small scale. I mentioned that the actual utilization of this area depended on the coming of the grid. Without the grid there would have been no Galloway water-power scheme, and, conversely, without the Galloway scheme the grid line would not have passed through this particular area at such an early stage as it did. The scheme has therefor involved considerable incidental advantage to the district. It includes a considerable amount of tunnelling, and, with a view to utilizing the electricity supply of the grid for construction purposes, the grid line was run through the district in advance of the construction. The large quantity of power required for air compressors for drilling and for rock-crushing and other work was then taken from the grid. As soon as the grid arrived, of course, the local authorities—the Kirkcudbrightshire County Council, the Dumfries County Council, etc.—initiated schemes for distribution, which were put in hand in most of the district. Thus the greater part of the district has already been electrified from the grid, steam power being imported until the water power stations are completed and ready to supply power themselves. The possibilities of demand in the district, however, are small in relation to the total output, and reliance is placed on the grid to transmit roughly half of the power northwards into Mid-Scotland and half southwards into North-West England for the purpose of taking off, particularly in the winter time, the upper peaks of the industrial day's load, thereby improving the load factor on the steam system. There is another point which I should like to mention in connection with the load factor. The capacity of the turbines for consuming water and turning it into electric power is approximately four or five times the average flow of the rivers, and this means correspondingly that in the case of heavy run-off, minor floods, etc., the flood water to that extent can be run through the turbines and turned into power. If desired, the turbines can be run during the night to utilize flood water, and with such a plant capacity the factor of utilization becomes a very high one. Mr. Halcrow mentioned that with a properly-financed hydro-electric scheme, with a sinking fund which will substantially wipe out the capital cost in 60 years (in most future schemes the Government will, I think, make the condition that it shall have the option of taking the scheme over in 60 years' time), the power will eventually be obtained for a very small figure indeed. There is another incidental advantage in the water-power schemes, to which I believe the authorities of the Central Electricity Board are quite alive, and that is that in all those cases where there is storage, whether it be seasonal or on a smaller scale, and where the supply is carried direct from the reservoir to the power station by means of a closed tunnel or pipe-line, in those periods when the stations are not running or not running to full capacity they act as a very efficient and immediate standby in the case of any breakdown of a steam machine or of a line elsewhere. They are immediately available simply by opening up and starting the machine. I have read with very great interest the authors' description of the two stations of the Grampian scheme—Rannoch and Tummel. I should like to ask them one question. In the one case there are vertical machines and in the other case horizontal machines. In the case of the Galloway scheme, for all the power stations, whether low-head (65 ft.) or high-head (up to 400 ft.), all the machines are vertical. No doubt there is some good reason for having horizontal machines in the Tummel station, but I should be interested to know what it is.

**Mr. P. W. Seewer:** I should like to correct the statement that the findings of the Parliamentary Commission are that the total output obtainable from water power in Great Britain would only be about 195 000 kW; my company has built and/or is about to install hydro-electric machinery which appreciably exceeds 300 000 h.p. in Scotland alone. It is interesting to note that the greater part of the machinery installed at the stations described by the authors is entirely British, in both design and manufacture. Hydro-electric machinery up to the largest sizes can be built with success in this country, and need no longer be purchased from abroad.

**Mr. E. Kilburn Scott:** The Cwm Dyli power house of the North Wales Power Co. was the first hydro-electric installation in Great Britain to utilize a high-head fall. Lake Llydaw is 1 416 ft. above sea level, and the drop to the power house is about 1 150 ft., giving a pressure of about 500 lb. per sq. in. at the Pelton-wheel nozzles.

I should like to give some particulars of how the Snowdon power scheme started. In 1903 I was doing some engineering work for the late Mr. Walter Harper, who was interested in promoting companies of an engineering character. Having been informed of the existence of water power on Snowdon, he asked me to report on the possibilities.

While making a survey of the Snowdon district I met Mr. Gethin Jones, who had for some years, on his own initiative, been taking rainfall records in Snowdonia. He gave the average annual rainfall at Lake Llydaw as over 180 in., and that at Glaslyn as 12 per cent higher. Features which made the proposition attractive were the natural storages of Lakes Llydaw and Glaslyn, and the steep and long drop into the valley.

Having made measurements of the flow of water from the lake under various weather conditions, I reported that, allowing for the friction in the water course and for a suitable pipe-line, a power plant of 6 000 h.p. was feasible. A high-voltage 3-phase installation appeared to be the most suitable type to adopt, because the most likely loads were at various slate quarries 10 to 20 miles away in different directions.

On visiting these places, I found that the working hours for machines were only about 6 per day and that, in the winter months, there were many short-time weeks. These conditions, and long week-ends, gave considerable periods for the accumulation of water. Soundings showed also that water could be drawn off about 20 ft. below the normal level of Lake Llydaw.

The next job was to raise capital, always a tiresome business, and especially so for an entirely new departure, as a public hydro-electric power supply then was. The simplicity of harnessing a high-head fall was not generally realized. For a given power, the amount of water is inversely proportional to the head; and therefore, although a river with a 10-ft. fall may be impressive, a small mountain stream having 10 times the head is a much better proposition. I was asked to demonstrate the possibilities to a financier who was interested in the scheme. When we started from Euston the weather was fine, but beyond Chester I was glad to see the rain; as we approached Snowdonia it increased, until at the lake there was a deluge. Water runs off quickly from the rocky slopes of Snowdon, and the stream was therefore in fine spate. I made some water measurements, explained my calculations, and, the elements being so propitious, had no difficulty in proving the estimate to be conservative. In due course the financier informed friends, and money began to come in.

The harnessing of the Cwm Dyli water power has been fully justified, and there is now 8 000 kW of plant in the power house. The success of the scheme led to other water-power developments, at Dolgarrog and Maentwrog. To-day, the slate quarries of North Wales are as well equipped as any in the world, partly owing to the fact that cheap electric power is transmitted to them from Cwm Dyli and Dolgarrog.

I should like to mention that engineers abroad meet with difficulties of which we are free in this country. For example, in colder countries there is "jelly-ice," which at changing seasons may clog screens and turbines. In most countries the distances over which current has to be transmitted to tap paying loads are much greater than in this country. Again, in warm climates there are difficulties due to lightning storms.

[The authors' reply to this discussion will be published later.]

## SCOTTISH CENTRE, AT GLASGOW, 13TH NOVEMBER, 1934.

**Mr. N. C. Bridge:** There is one matter in this paper that interests me particularly; that is, the comparisons that are made in one or two places with coal stations. If we could superimpose upon Fig. 1—the rainfall map of Great Britain—the areas of the coal-fields of Great Britain, I think we should find in Scotland a surprisingly large amount of overlapping of high rainfall and coal supplies. I doubt whether there are any other parts of the world that could show this in the same degree; but if there are, I do not think those countries can have the same facilities for development as we have here in Scotland. Scotland is therefore probably one of the most favourably placed countries in the world for the combined hydro-electric and steam generation of electricity. There is a reference in the paper to the proposed method of working the new stations of the Galloway concern in conjunction with the steam stations of the Central Scotland area, and in that connection I think there is one point that might receive further consideration. It is suggested that these Galloway stations shall be operated so as to improve the general load factor of the steam stations; but to get the best out of the steam stations is not just a matter of improving the general load factor. What we really want is to flatten out the load curve throughout the day. Those who have had anything to do with the operation of steam stations will know very well the loss of thermal efficiency that occurs owing to the load changes from hour to hour or from minute to minute—the losses due to keeping banked boilers standing by for emergencies, those due to the putting on and taking boilers off the line, and those due to starting up and shutting down the turbines. If we could run these stations at constant load, so that adjustments are not necessary in the firing of the boilers, which is one of the most serious sources of inefficiency, we should be able to show remarkably good results for the combined generating costs of the hydro-electric stations and the steam stations. Of course, we must have complete confidence in the transmission lines connecting the various stations to the grid, but though ours was the first of the regional systems to be put into operation it has, I think, shown a very creditable performance so far. We have now been operating for some 3 or 4 years without any disturbance of a major nature, and I think that reflects great credit both on the Central Board control and on the station operators.

Another point that rather interested me was the reference to the screens at the intakes, and to the special material used for the runners of the turbines of the Grampian stations (special alloy bronze at Rannoch and chromium stainless steel at Tummel). This is a reminder that even the hydro-electric stations are not employing a perfect working fluid. Those who are more closely associated with the steam stations know very well what we have to contend with in regard to impurities in the working media in that case—ash and grits, water vapour and sulphur compounds in the flue gases, oxygen and chemical impurities in the feed water, and water droplets, etc., in the steam, where they are not wanted. Also, in the circulating-water system we have foreign matter to contend with—solids, air released by the pumps, and chemical or algæ matter which impairs the condenser heat transmission. It is thus of some interest to know that the hydro-electric stations have to make certain special provisions against foreign matter in their single, simple working fluid. I should like to ask the authors what their experience has been with regard to the costs of maintenance and attendance for these screens, and whether the special materials adopted for the turbine runners have been entirely satisfactory in eliminating pitting due to the erosive action set up by released air or other impurities in the water.

The only other point I might mention—perhaps rather a trivial one—is that on page 132 the authors use the term "h.p." for the output of the Grampian plant, though elsewhere the outputs are given in kW. We as electrical engineers have not much use for the term "h.p." in these days, and I would much prefer that we should only have to think in kW.

**Mr. W. J. Cooper:** It is gradually becoming recognized that we may have other things to do with our coal besides burning it in a boiler. I have a notion that in the future our thoughts will turn more towards using natural power in its elementary forms. For that reason I think that hydro-electric development is of fundamental importance. It seems to me that in the future the most active localities in the world will be those situated in areas where high altitudes and steep gradients prevail. Have the authors in their experience discovered the practical economic limit of the transmission of power over considerable distances? What I am thinking of is the question of whether the hydro-electric schemes of Scotland are likely to be used for the transport of energy to distances remote from the source of generation, or whether industrial activity may be initiated farther north than is the case at present.

**Mr. A. P. Robertson:** The Rannoch station has vertical turbines and the Tummel station has horizontal turbines. I should like to know whether there is any reason for the difference in the type of plant employed, namely, vertical and horizontal. The vertical type seems to possess one advantage, and that is that the bearings are more easily looked after. I think I have heard it stated that there is some considerable difficulty in lubricating bearings of the horizontal type, owing to the very great weight. I should therefore like to know the reason for the adoption of the two types, and whether it is in the nature of an experiment or the result of experience.

**Prof. F. G. Baily:** If the map of Scotland is examined, it is found that most of the population lives along the coal belt. This grouping is not due entirely to the coal, however, for the east coast up to Aberdeenshire is well populated, though there is no coal beyond Fife. The ground is reasonably level and is fertile, and this is also the case along the coal belt. To argue that the hydro-electric power in the Highlands will allow of a large industrial development there ignores the unsuitable character of the ground. There is no food, there is little level ground, and communications are restricted to the lower end of the valley, as the sides and top end are impossible for railways and difficult for roads. Except where electric power is the chief item in the cost of manufacture, as in the aluminium works, it is far more economical to transmit the power to areas more suitable for industry. This brings the electric power into competition with the coal-fields or with sea-borne coal, and its financial advantage becomes precarious. Mention has been made of the use of hydro-electric stations for peak loads. This is a strong point if the distance of transmission is moderate, but transmission costs rapidly increase with low load factors, so that long-distance transmission of peak loads is uneconomical.

The paper is completely lacking in information about costs of construction, which is the first thing one wants to know in regard to a hydro-electric scheme. Before any further schemes are undertaken the costs of the present ones should be disclosed. Figures for the Kinlochleven and the Clyde Valley plants are known, and the first are very favourable, as the conditions are exceptionally good. The Clyde Valley plant is also on the right side, though not by very much. There is reason to doubt, however, whether the others will be able to compete against coal stations of modern type that are provided with cheap coal; and in their own areas the hydro-electric stations have only a very small population, while the new schemes which are in possible prospect are in areas more remote and devoid of population or means of access.

**Mr. H. M. Stronach:** None of the previous speakers has mentioned the possibility of distribution breakdowns. The authors' slides show that the double-circuit lines run through very difficult country, and I do not suppose these lines can operate without a breakdown. One of the main points in favour of overhead construction is the rapidity with which repairs can be effected. The Central Scotland scheme has been in operation for some time, and, although there has not been any very serious trouble, one or two little mishaps have occurred which have not been dealt with as quickly as one would expect with overhead lines. Possibly weather conditions are to blame for this. When a breakdown occurs during foggy weather in wild country such as that illustrated in the slides, it takes a long time for the repairers to reach the fault, and when they do reach it they have to work under very difficult conditions. It seems to me, therefore, that an output of, say, 30 000 kW might be suddenly cut off for two to three days because of the repairs difficulty. I should like to have the views of the authors on this point, and I should also like to know whether any trouble has been experienced on the lines feeding into the grid supply.

[The authors' reply to this discussion will be published later.]

## SOUTH MIDLAND CENTRE, AT BIRMINGHAM, 19TH NOVEMBER, 1934.

**Mr. William Wilson:** The paper forms a very complete record of the work carried out in connection with the Grampian scheme, and will be valued accordingly by those engaged in this particular type of work. For the great number of electrical engineers interested in the subject, especially in the general question of hydro-electric development in Great Britain, a more critical and analytical treatment would, however, have made the paper much more amenable to discussion. As regards the future of hydro-electricity in England, and possibly even in Wales, Table 1 does not at first sight appear to hold out very much promise. In England, for example, the total possible output of the whole country does not exceed half the capacity of a single steam generating set such as that now being installed in Birmingham, and I should like to ask the authors whether the economic position of any of the projects is sufficiently favourable to justify development on such a small scale as the figures indicate. The basis for evaluating a hydro-electric scheme is laid down on page 130, where it is stated "it must be demonstrated that hydro-electric power in any given instance can produce power at any rate as cheaply as an alternative supply from coal on the same site." I wish the authors had afforded us some basis for considering the subject by including in their paper the necessary costs. For the Welsh plants quoted on page 131, I believe the costs of producing power are about 0·06d. per unit sold for Cwm Dyli, 0·05d. for Dolgarrog, and 0·025d. for Maentwrog. Dealing with the latest and most economical station, the capital cost of the whole plant was about £1 million, working out at between £40 and £45 r kW installed. Of this, the cost per kW for plant, undations, and building, was £6, which may be com- red with the corresponding figure for steam stations about £15 per kW. I believe, however, that a comparison of the cost per unit with that of power available from the grid is not sufficiently favourable to justify any further hydro-electric development, at any rate in the near future. I should be glad to know whether the authors agree with the latter statement, as it would appear to condemn the possibility of further hydro-electric enterprise in England and Wales. It would be very interesting if they would also give us the broad economic requirements for a British hydro-electric scheme to be a paying proposition. My own contention, based on a considerable experience of hydro-electric development in both hemispheres, is that such work is usually much assisted by its psychological aspect. When a steam station is proposed, conservatism has to be overcome before the necessary support is received; but when a hydro-electric enterprise is set on foot the public are always conscious that they are about to take advantage of power that is running to waste, and are going to get something for nothing, so that a much more ready and enthusiastic response is accorded to such proposals. In consequence, schemes are put in hand which otherwise would either have not materialized or would have been supplied by means of steam. Further, sufficient support is received for the plant to be made of relatively large capacity, and prospective users are much more ready to come forward with a demand for power, because they think it is going to be cheap. This is all to the good, but it leaves one with the suspicion that existing hydro-electric concerns might in a number of instances have been less economical than steam stations if the necessary support for the latter had been forthcoming. On page 131 the authors make a very brief reference to the Severn scheme, and state that the estimated capital expenditure exceeded £38 millions. This information has no particular value without some estimate of the magnitude of the scheme. I should have liked to have seen this scheme described at greater length, and the present position summarized, as it was my impression that the actual cost per kW was remarkably low, and that the amount of power available would have rendered the scheme an economical proposition.

**Mr. A. L. Coward:** I have been greatly impressed, in reading the paper, with the care which has been taken to develop the protective system of the Grampian scheme, not only on the electrical but also on the hydraulic side. Indeed, the precautions are so thorough that there appears no chance of the machines misbehaving.

The figures given by the authors indicate remarkably good governing on load; even when full load is thrown off, the momentary rise in speed is stated to be only 17 per cent. If a site test was carried out, I should like to know what was the rise in voltage of the alternator when this full load was thrown off.

With towers carrying four circuits, the transposition of the circuits presents unusual features. I am disappointed that no lantern slide of a transposition tower has been shown.

Since the main sets are provided with a brake for bringing them to rest quickly, could the authors quote the figures of the time taken to come to rest, after the main valve has been closed down, with the brake applied and also without the use of the brake? With such heavy rotating parts, the use of the brake appears essential. Were the rotors tested to any predetermined overspeed at the works or on site?

**Mr. H. S. Davidson:** The authors refer to the special precautions which have been taken—in designing turbines—to deal with the possibility of erosion, but beyond the use of bitumastic paint I cannot find that any similar precautions have been taken with regard to the pipe-lines. Do the authors anticipate any erosion in, or on the outside of, the pipe-lines? It is appreciated that the atmosphere in the North of Scotland is not like that in Birmingham, but it does seem to me that perhaps some special precautions might have been taken with regard to the choice of metal used for the pipe-lines.

**Mr. R. H. Rawll:** There appears to be only one connection of the Grampian scheme with the grid of the Central Electricity Board. It would be interesting to learn whether the policy of the Board, as regards future development in the North of Scotland, will be to leave to the Grampian Electricity Supply Co. the interconnection of any other power stations erected by that company in the future, or, alternatively, whether it is proposed to extend the grid lines for this purpose. Owing to the comparatively small power output available in the area, it would seem to be decidedly more economical to adopt the former proposition.

[The authors' reply to this discussion will be published later.]

## NORTH-EASTERN CENTRE, AT NEWCASTLE, 26TH NOVEMBER, 1934.

**Mr. F. C. Winfield:** One must agree with and welcome the authors' survey of the water-power possibilities in this country, if only because there is so much vague talk from time to time in the Press and amongst the general public and engineers about the wonderful potentialities of water power and the low cost at which power can, they estimate, be obtained from water in this country.

The authors show that the total power available from water in the United Kingdom is estimated at 250 000 kW, which is about equal to the capacity of the first Barking power station. Of that the authors have already absorbed, or are going to absorb, about two-thirds. A few other supply undertakings seem to have nearly exhausted the remainder. The authors' special plea for the consideration of the use of water rather puzzles me, because there does not seem to be any water left to use.

Regarding the actual cost of power obtained from water, there are cases where water power can be obtained very cheaply, but, in general, I think there is very little difference in the costs of power obtained from steam and from water. Speaking very broadly, the total cost of power obtained from coal is more than twice the capital charges, and the capital charges on water-power stations are something approaching twice the capital charges on the steam power scheme. Usually the water-power scheme is saddled in addition with considerable transmission costs, because it is only rarely that the power is available close to the load; so that there is really no great difference between the cost of power produced from water and that produced from steam, and that is probably why we find that water power has been so slow in developing. Except in minor instances, it has always needed some assistance from some other conditions. The Welsh scheme developed originally from some local power, and was assisted to go on by larger power schemes. Although the Scottish Highlands scheme is able to supply the grid with some power, it is actually carried on the back of local electrolytic works. The Galloway scheme is justified because it supplies peak-load units and really in some small measure meets the need for that thing which we lack most in electric power supply—power storage facilities. The Severn scheme seems to be justified only if the railways and roads will bear some considerable part of the capital costs.

It seems fairly clear that water power on a large scale in this country is not primarily economically possible. I do not see why we should pay other than special attention to this, except for the important point that its development in this country has enabled the manufacturers to get some experience which they can use in competitive contracts abroad.

Perhaps in my very rough comparison of the cost of steam and water I should have mentioned that in water-power schemes the life of the plant is almost indefinite. Forty years is quite a moderate life, unless methods of using power vary very much in the future, whereas for steam power schemes obsolescence is probably a matter of about 25 years.

There is need in this country for more facilities for hydraulic testing. Our manufacturing firms cannot produce and test a model design of the works which they propose. In other countries hydraulic testing for water-power schemes is associated with tidal and river works and similar investigations which are just as useful in this country as abroad; and therefore there seems to be good reason for a hydraulic testing laboratory in this country. The absence of such a laboratory handicaps our manufacturers. Anything the author can do in that direction would be worth while.

I must sympathize, from my own knowledge, with the authors' remarks about the high cost of Scottish sporting rights associated with any water-power development. Regarding amenities, I have seen many water-power schemes, but I have never seen one which, in my view, in any sense detracted from the landscape or in any way hurt one's æsthetic feelings.

I should like to have the authors' experience of a number of minor details, one of which is freezing. In the schemes with which they have been associated, have any troubles arisen from this cause, and have any special features been incorporated to avoid the trouble? I should like to know how often the authors find it necessary to clean screens, whether daily or weekly, and whether there is much seasonal variation in this. I note that the steel pipe-lines have been painted with bitumastic enamel, and I should be glad to know whether this has proved satisfactory in practice. What is the authors' experience with the special alloy bronzes and chromium-steel runners to which they refer?

The 4-circuit overhead power line shown in Fig. 16 is very interesting, and I should be glad to know whether it has been found in practice that the lower 33-kV lines have been more immune from lightning disturbances than the others.

I should also like to know whether the graded air-gaps used near the terminal points have resulted in more frequent outages of the lines owing to the reduced flash-over voltage.

**Mr. W. D. Horsley:** The authors point out (page 130) that with continuous operation at a high load factor, hydro-electric energy is more economical than electrical energy produced by a steam plant, whilst the latter is the cheaper at low load factors. It is also stated that the Galloway power scheme is intended to supply peak-load power to the main system, and under this condition of operation the load factor must be low. Would it not have been more economical to have supplied the peak load by means of extensions to existing steam stations?

The speed regulation of water turbines is less sensitive than that of steam turbines, and it would be of interest to know whether any operating difficulties have been experienced for this reason. The rise in speed when full load is thrown off is given on page 138 as 17 per cent; what is the rise in voltage and what is the effect on local load? It is noticed that the transformer voltage tests given on page 143 are higher than normal, which may be to provide for an abnormal rise in voltage when throwing off load.

It is stated that dual-purpose exciters are provided for the alternators in the Rannoch power station. Does this mean that the main exciters are provided with auxiliary exciters, or that the exciters are actually used for purposes other than excitation?

It would be of interest if the authors would give the method adopted and the power taken in starting the Tummel alternators when they are required for operation as synchronous condensers disconnected from the turbines. Why is provision made for the alternators to be run as synchronous condensers either coupled or uncoupled from the turbines?

The capacitance bushing earthing device at Abernethy, which is shown in Fig. 18, does not appear to be mentioned in the text. It would be of interest to have details of this apparatus.

**Mr. D. E. Lambert:** With reference to the purely electrical engineering side of the paper, it is interesting to note that the breaking capacity of the oil switches at Rannoch and Tummel power stations, given as 750 000 kVA, provides an ample margin of safety over the worst fault condition. Taking the ultimate plant capacity as given by the authors, at Rannoch—since there are no feeder circuits as distinct from supply circuits—the worst condition would be the occurrence of a fault on one of the 11/33-kV lines, which would give about 650 000 kVA. A fault on one of the machines or the 11/132-kV line circuits would be less severe, namely in the region of 575 000 kVA. At Tummel the worst fault appears to be less by about 100 000 kVA than the corresponding condition at Rannoch. At this station the feeds from the main 11-kV busbars to the auxiliary 11-kV switchgear do not appear to be protected by circuit breakers. Thus, a fault on one of the reactors would bring out all the main circuit-breakers at Tummel. It would be interesting to know whether this is a temporary arrangement only.

The question of automatic load and frequency control is dealt with rather scantily in the paper, and the statement is made that automatic frequency control can be used as an alternative to load control. Without further explanation as to the exact load-control scheme adopted, it would appear that both automatic load and automatic frequency control are necessary to ensure correct frequency under varying load conditions. The scheme mentioned in the paper for frequency control bears out this contention, since it is stated that load control is automatic only when the frequency is maintained within pre-adjusted limits. It would be interesting to know the results obtained with the schemes mentioned, and also what means are used for maintaining frequency within predetermined limits.

The authors state that the turbine governors at Tummel are of the oil-operated type with double compensating gear to prevent hunting, but when describing the automatic synchronizing gear they state that a special hunting relay is introduced to initiate what one might call colloquially a "hit and miss" arrangement, consisting of hunting on either side of the correct synchronizing speed until the incoming machine is in phase with the busbar supply. This method is no doubt effective, but it appears to be rather indefinite, particularly when there are a number of schemes in use for the purpose of precise automatic synchronizing. One, for example, utilizes only five relays for comparing the phase and speed of the incoming supply with the busbar supply, and also for giving impulses to the governor motors, these impulses being arranged to be less frequent as the incoming machine approaches synchronism. One advantage of this particular arrangement of relays is that it can also be employed for automatic frequency control by comparing the supply frequency against the standard frequency.

One of the outstanding points of interest in this Grampian hydro-electric development scheme is the provision of supervisory control and telephony equipment for superimposing signals on the main power lines. In this connection it is stated that superimposed telephony is carried out between Rannoch and Abernethy over the 132-kV overhead line and it is intended to extend the supervisory control equipment to control the Rannoch station. It would be interesting to know whether it is intended to carry out this superimposed control over the 132-kV line from Tummel to Rannoch, or, alternatively, over the 33-kV line. The former would appear to have theoretical advantages, but there may be practical considerations of which the authors are cognisant and which may influence the decision otherwise.

[The authors' reply to this discussion will be published later.]

## MERSEY AND NORTH WALES (LIVERPOOL) CENTRE, AT LIVERPOOL, 3RD DECEMBER, 1934.

**Mr. R. G. Devey:** The masterpiece of the work described by the authors is that on the civil engineering side. While the paper was being read I could not help making a mental note of the difficulties met with in this class of work—the hilly and mountainous districts, tunnelling, watershed areas, the travelling of miles upon miles of difficult country, the investigation of difficult land, and the amount of pioneer work which is necessary before a scheme is finally decided upon. (A comparison may be made here between the size of the small piece of land required for an ordinary steam station, and the much larger area required for a hydro-electric installation).

The subject of water power is of great interest to this centre as we have in this area a well-developed water-power scheme—that of the North Wales Power Co.—for which Mr. Paton is largely responsible.

**Mr. G. K. Paton:** The paper is not complete without some reference to the difficulties met with during construction, and the means of overcoming these difficulties in transport by the construction of roads and railways with their complement of camps for the workers. I am glad that the authors have shown some lantern slides which enable one to appreciate some of these difficulties.

The original development at Dolgarrog in 1909 utilizes surplus water from Llyn Cowlyd, but the main source of supply was Llyn Eigiau.

Reference is made in the paper to the turbines installed at Rannoch, the runners of which are of special alloy bronze, whereas the Tummel machines have runners of stainless steel. In Wales, as a result of experiments carried out over a number of years, we have definitely decided upon the use of stainless steel as being the most suitable material, particularly on high-head work. The needle heads and nozzles are of stainless steel, and in the smaller machines the buckets are of solid stainless steel. In the larger machines the cast-steel buckets are faced with stainless steel, electrically welded.

Referring to Tables 3 and 4, the figures for the kW capacity installed in the various stations are misleading, as they do not represent the 100-per-cent load-factor output of the watersheds. For instance, in Table 3 the output represents, with the maximum plant capacity installed (which is the maximum load), a load factor of under 25 per cent. Table 4 can be improved by an additional column to give the 100 per cent load-factor capacity in accordance with the standard method for the rating of watersheds.

In referring to the present situation in Great Britain, some reference might have been made to the gross inequalities of rating imposed upon hydro-electric undertakings in this country. Under present methods the rating is determined by the *cumulo* net annual value of the undertaking; and whereas in a steam station the average assessment is about £12 per £100 of the gross revenue, in a hydro-electric undertaking the equivalent is about £35 per £100 of gross revenue, or £43 per £100 of net revenue.

No reference is made to the amount of storage available in the Grampian scheme, but it is evident from the figures given for the catchment area that the storage available is not consistent with what would normally be required in a similar station not connected with the grid system of the Central Electricity Board. We have found by experience that the storage required to enable the output to be averaged throughout the year represents approximately one-third of the average rainfall within the catchment area, and it would be interesting to know the amount of storage available for this particular scheme in terms of cubic feet or kilowatt-hours.

Reference is made to the guaranteed efficiency of the turbines and generators, and it would be of interest to know whether these guarantees have been obtained and also the methods adopted for checking the water consumption.

The paper is not complete without some reference to the actual cost of the works as affecting the operating cost in capital charges. Although the operation cost without capital charges may be very low, possibly in the region of 0·025d. per unit, it would be of interest to know the total cost per unit, including capital charges.

Dealing with the electrical side, there are one or two points on which information is required. Boosters have been installed with on-load tap-changing by remote control from the power station. I gather that it was decided to keep the main transformers free of tappings, but the introduction of a booster equipment appears to be more likely to weaken the system than would the use of tap-changing on the main transformers. It is noted also that the neutral points of the 132-kV system are earthed through a resistance, whereas on the grid system the earthing is direct. A voltage of 440 volts also appears to be used for the secondary supplies, instead of the standard 400 volts.

It would be interesting to know why the Hewlett type of insulator has been used on the transmission lines in preference to the standard cap-and-pin type, which has been proved to give excellent service as regards mechanical strength.

Another feature in which the Grampian scheme differs from the grid system is in the addition of a series of graded arc-gaps as protection against lightning. It is not stated how these gaps function, and what there is to prevent a dead short-circuit to earth.

The authors mention that the 33-kV lines are carried for a distance of approximately 60 miles. This appears to be an excessive length of transmission for 33-kV operation, and it would be interesting to know whether supplies are available at intermediate feeding points.

**Mr. G. E. Swift:** Hydro-electric power in England is rather overshadowed by the developments in Scotland and Wales. There are rivers in England which are eminently suitable for the development of low-fall water power, and which could be economically utilized for the efficient generation of electrical energy. The authors say that 20 000 kW is available; such an amount of power would be very acceptable in sparsely populated areas for the revival of rural industries and for localized rural electrification. It is to be hoped that, when this shadow has passed over, something will be done to investigate the possibilities of these rivers. I should like to refer to the Chester hydro-electric works; this scheme was originally for direct-current output, but to meet the requirements of the change-over to alternating current a motor-generator has been installed and the plant now feeds into the general network operated from the grid. This station, during 21 years of operation, has generated over 30 million units with a repairs bill averaging £50 per annum. There are two points on the technical side on which I should like some information. With regard to the abnormal voltage-surge protection afforded by a series of graded arc-gaps, do the latter operate effectively? I should also like particulars of the general design of earthing connections in difficult situations.

**Mr. H. Gill:** The authors quote particulars of the storage capacities of Loch Ericht and of the Blackwater reservoir in the adjoining watershed, these being approximately equal. As the respective catchment areas are 185 and 55 square miles, there is a considerable disparity between the two developments in regard to the ratio of catchment area to storage, which requires explanation.

In the case of the Tummel scheme, only a small amount of storage has been obtained by raising the level of Loch Rannoch 8 ft., so that much will depend on the spread of the rainfall throughout the year as to the best possible utilization of the waters from the area. As it is usual in the British Isles for the greater part of the annual rainfall to take place during the winter months, when the percentage run-off is high, a larger generating plant at the Tummel station would appear to have been justified. The efficiency of the turbines at the Rannoch station, 90·5 per cent, is noteworthy, and it would be of interest to know what steps were taken to ensure accurate measurement of the water consumption during the tests. The use of rollers for supporting the pipes has certain advantages over the usual method of concrete piers constructed close up to the pipe. It is doubtful, however, whether the use of the roller support should permit of any material reduction in the size of the anchor blocks.

The method of operating the hydraulically-operated throttle valves at the tunnel outlet appears to be a new departure, since the equipment comprises an electrically-driven oil pump, with a Pelton wheel as stand-by, whilst the valve is actuated by oil pressure from accumulators. The arrangement appears to be much more complicated than the ordinary butterfly valve arranged for closing by weights, which, owing to its simplicity, is less likely to fail in case of emergency. There would appear to be no good reason for the additional cost.

As regards the aqueduct, no mention is made of any spillways or sluices for scouring purposes, and it would be of much interest to know what happens to the water flowing in this canal in the event of the load being suddenly thrown off the station. Also, what means have been provided for removing the silt, etc., which must inevitably find its way down to the forebay?

The reason for the elaborate nature of the works at the intake dam is not clear, and it would be of interest to know why the arrangement of sluices and siphons was adopted in preference to a spillway dam with sluices controlling the flow to the aqueduct only.

**Mr. O. C. Waygood:** A paper on development is not complete without some reference to the economics of the subject, and if the authors could add an appendix giving some indication of capital costs per kW installed, and also generation costs, the value of the paper would be considerably enhanced.

Published statistics bearing on the costs of generation suggest that the cost of coal does not, to any marked degree, influence the generation cost of the unit. The slides shown and the particulars given in the paper suggest a very heavy capital outlay, both in labour and in material, which must ultimately affect the general costs.

**Mr. C. R. Bolton:** I should be glad to have an explanation of the principle employed in the protective device, mentioned on page 153, which comes into operation when the turbine-governor belt breaks.

[The authors' reply to this discussion will be published later.]

# TELEGRAPHY AND TELEPHONY.*

By B. S. Cohen, O.B.E., Member.

## Introduction.

During the past three years technical development in the art of telecommunication has shown many interesting features, although to a considerable extent the economic situation has delayed the introduction into practice of certain important developments.

The two tables of wire mileage for Great Britain only, included in previous reviews on this subject, are replaced in this review by Table 1, which gives some comparative information with regard to the total single-wire mileage of trunk and local telephone aerial wire and underground cable and telegraph wire for Great Britain, U.S.A., France, Germany, Switzerland, Sweden, Denmark, and Italy.

## Telephony.

### *Recent Technical Developments.*

*"On demand" system.*—In Great Britain one of the most important developments has been the introduction of the "on demand" system of working, by means of which the subscriber can obtain his trunk communication directly as in the case of local calls. As a result, the trunk exchanges at zone centres and most group centres have had to be reorganized. The cord circuits and line terminations have been redesigned on the sleeve control system, which speeds up the operating by providing increased facilities. The cord circuits are of a universal type with no transmission bridges; these latter are on the line terminations, which provide the signalling facilities required for the various types of lines, and operate the supervisory signals via the sleeve connection of the cord circuit. The toll circuits, inland trunks, Continental trunks, and radio links, in the new Faraday Building in London are all equipped on the sleeve control principle.

The introduction of the "on-demand" system has necessitated very considerable increases in the number of channels of communication between centres, and the speeding-up of the operating times as much as possible. The fact that this system is now in operation over a substantial percentage of the trunk and toll circuits, and that, in addition, it has been found possible to make considerable decreases in the fees for inter-urban communication, is an indication of what can be done by careful application of the technical and economic possibilities of recent telecommunication engineering developments. A brief description of some of the more important of these developments follows.

*Telephonic repeaters.*—Repeater design has been improved in a number of minor directions, and the summation of these improvements has resulted in very considerable economies in first cost and maintenance.

The extensive use, for example, of lower-filament-consumption valves, saving 0·75 ampere per repeater, has enabled considerable extensions of repeater-station plant to be made without corresponding increases in power plant. In commercial telephone systems, valves must have stable characteristics for very long periods of continuous service. Hitherto, this has been largely achieved by using valves consuming about 4 watts in each filament. Oxide-coated valves are now more exclusively used; the filament of this type of valve consumes 1 watt or less, while the expected stable-life period should be not less than 1 year of continuous running. The filaments are directly heated with unrectified alternating current, the grid priming being obtained from a voltage-drop in the anode circuit. With these changes, improved values of mutual conductance have also been obtained.

The manufacture of the simplified repeaters and amplifiers for unattended stations has been proceeding at a rapid rate. There are in this country 43 repeater stations and 72 amplifier stations in operation. It has been quite practicable to employ receiving units only on the shorter lines where transmitting amplifiers are not justified.

The repeaters and associated equipments have been redesigned with components of smaller size resulting from the use of high-permeability magnetic material; and the standardization of equipment, mounted on one side of the panel only, has halved the space occupied per repeater.

The insertion of a cheap and simple repeater or amplifier into telephone exchanges through which toll lines pass has also resulted in considerable savings, and has rendered possible the use of 10-lb. conductors for short trunk lines and for long junction lines.

*Zero-attenuation circuits.*—A notable development in Great Britain has been the general adoption of the zero-attenuation circuit for all zone-to-zone trunks, which has been rendered possible by high-grade maintenance and by the general use of 600-ohm terminal stabilizing resistances. An essential feature of the zero-attenuation circuit is the use of an echo suppressor. Great Britain is the first country to introduce zero-attenuation circuits into general service, and the cord-circuit repeater is now rarely used here.

*Two-wire zero circuits.*—The adoption of 2-wire circuits of zero attenuation is now contemplated as a result of recent investigations, and it is anticipated that a substantial percentage of long-distance 4-wire trunk circuits in this country will be capable of conversion to zero 2-wire working, thus giving a considerable increase in available channels. This important development has resulted from recent improvements in echo suppressors and stabilizers.

*Application of metal rectifiers to long-distance telephony.*—A combination of metal-rectifier elements can be used as a variable attenuator or switch in an a.c. signalling

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* A review of progress.

TABLE 1.

| | Great Britain, as at 31.3.34 | U.S.A.,* as at 31.12.33 | France,† as at 1.1.33 | Germany,‡ as at 31.3.33 | Switzerland,‡ as at 1.1.33 | Sweden,†† as at 31.12.33 | Denmark,† as at 31.3.33 | Italy,§ as at 30.6.32 |
|---|---|---|---|---|---|---|---|---|
| | miles | miles | miles | miles | miles | miles | miles | miles |
| *Trunk telephone lines* | | | | | | | | |
| Open wire .. .. .. | 479 510 | 2 757 000 | 1 272 000 | 742 000 | 43 200 | 287 034 | 202 500 | 197 500 |
| Aerial cable wire .. .. | | 5 751 000 | | 33 600 | 357 000 | 362 998 | 264 800 | — |
| Underground wire .. .. | 1 909 524 | 6 745 000 | 822 000 | 2 710 000 | | | | 145 000 |
| Submarine wire .. .. | 20 005 | — | 9 270 | 45 000 | — | — | 11 700 | 740 |
| *Exchange telephone lines* | | | | | | | | |
| Open wire .. .. .. | 666 881 | 1 975 000 | — | 1 000 000 | 76 000 | 791 361 | — | — |
| Aerial cable wire .. .. | | 16 997 000 | — | 560 000 | 2 620 | | — | — |
| Underground wire .. .. | 7 944 117 | 46 056 000 | — | 10 280 000 | 698 000 | | — | — |
| Submarine wire .. .. | 1 044 | — | — | — | — | — | — | — |
| Total (U.S.A.) as at 1.1.33, | | 87 678 000‖ | as at 1.1.33,‖ except Germany, Sweden, and Denmark** | | | | | |
| *Telegraph wire* .. .. .. | 331 656 | 2 260 000 | 523 000 | 134 000 | 16 000 | 18 833†† | 11 000 | 250 000 |

* Bell System only, except total figure, which includes the independent companies in the U.S.A.
† Figures according to *Europaischer Fernsprechdienst*, 1933, No. 33, p. 190.
‡ Figures according to *Journal des Télécommunications*, 1934, vol. 1, pp. 47, 190.
§ Figures according to *Europaischer Fernsprechdienst*, 1933, No. 32, p. 133.
‖ Figures according to American Telephone and Telegraph Co.'s Report for 1933.
** The miles of telegraph wire in Germany and Denmark are as at 31.3.33, and in Sweden at 1.1.34.
†† Figures according to "Résumé en Français de son Rapport de Gestion pour l'Exercice 1933," p. 19 (Direction Générale des Télégraphes de Suede.)

circuit by varying the impedance of the elements by means of a steady control current. The applications of the variable-attenuation network used as a voice-operated switch requiring neither additional valves nor moving parts for its operation, to enable highly efficient, simple, and cheap echo-suppressors, stabilizers, and loud-speaker telephones, to be constructed, have been developed and patented by Ryall. A brief description of one such application will be found in the *Journal*.*

*Carrier telephony*.—The application of carrier-frequency systems to suitable aerial lines and land and sea cables has received considerable attention. Metal rectifiers are now very frequently employed for the processes of modulation and demodulation. The simplified equipment employs fewer valves, and the initial costs and maintenance charges are very much reduced. The metal rectifiers so used are sometimes connected in a balanced form, and it can be arranged that, in the modulator for instance, the carrier frequency and the audio frequency can be suppressed, leaving only one side-band to be filtered out in the general case where the single side-band system is employed.

Simplified mains-operated equipment has been developed and is now freely in use in many places in this country. It is applied on aerial-line circuits up to 30 decibels attenuation, including short lengths of underground cable. For seasonal circuits and emergency conditions, such as special races and exhibitions, it is also valuable. In this equipment a carrier frequency of 6 500 cycles per sec. is employed and the two directions of transmission operate, one on the lower side-band frequency and the other on the upper side-band. Interference on these systems is small, and in general the circuits are quieter than their associated physical channels. In some cases four of these circuits are superposed on the same pole route, and it is then occasionally necessary to add further line transpositions and adjust operating levels to improve the cross-talk between the circuits. It may be of interest to note that one of these circuits operates between Inverness and Wick in Scotland with an overall attenuation of 3 decibels, and the circuit has enlivened trunk-telephone interest from the North of Scotland, which includes on occasions a "tourist" call from John o' Groats to Lands End.

On sea cables, with the growing telephone traffic loads, the provision of additional channels has been of prime importance. Certain multi-channel telephone and telegraph systems in America are well known. Between England and Holland six carrier telephone circuits have been installed on the two latest continuously-loaded paper-insulated cables. On one of these, four carrier circuits, eight side circuits, four phantom circuits, and four super-phantom circuits, are in operation on the four quads. A single-channel system is also installed on a similar cable between Blackpool and the Isle of Man.

In the case of gutta-insulated sea cables, in various parts of the world, multi-channel carrier working is frequently employed. Balata cables between the Isle of Man and Ireland are being used for a 3-channel system, which may possibly be extended to four channels, while between Scotland and Ireland a 3-channel system will be operated.

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* B. S. COHEN: "Research in the British Post Office," *Journal I.E.E.*, 1934, vol. 75, p. 144.

A submarine telephone and telegraph cable and associated carrier equipment between Australia and Tasmania which is now in course of construction introduces several interesting features, notably a coaxial-type cable with paragutta insulation in two lengths, each of 81 nautical miles, to an intermediate island (King Island) which will be utilized as a repeater station. The system will provide initially 5 telephone circuits, 7 telegraph circuits, and a one-way reversible broadcast channel. The cable and equipment are being supplied by British manufacturers.

On land cables extensive developments are in hand for providing single-channel carrier systems on existing and new circuits where the loading is sufficiently light. In this country the East Coast cable, from London to Edinburgh, has been reloaded with coils of 19 mH or in some cases 27 mH. On the West Coast route, from London to Glasgow, the old heavy-conductor telegraph cable has been loaded with 10-mH coils at 2½-mile spacing. In each case a cut-off frequency of about 7·4 kilocycles per sec. has been arranged to provide for operating on the lower side-band of the 6-kilocycle carrier frequency. The modulators and demodulators are of the balanced metal-rectifier type. Both audio-frequency and carrier channels will in general operate on the 4-wire basis, common amplifiers being employed and special means adopted to ensure that cross-modulation shall be satisfactory. Metal rectifier and resistance elements connected at the output of the repeater are arranged to improve considerably carrier-to-audio cross-talk, while the low hysteresis resistance in the loading coils caters for the audio-to-carrier direction in which cross-talk might occur on the same quad. In order that echo suppressors may be fitted they must be suitable for terminal working, and it necessarily follows that separate amplifiers must here be employed.

With the above scheme an audio-frequency and a carrier channel operate on one quad, the "go" pair taking audio and carrier in one direction and the "return" pair doing the same in the other direction. New main cables between London and Liverpool, and Liverpool and Glasgow, have been designed, containing 25-lb. lightly loaded conductors to enable this carrier system to be applied. The Liverpool–Glasgow cable is in process of installation.

Another method of single-channel carrier working which has been employed in Germany is the *zweiband* system* where each pair provides one circuit, one direction of transmission being audio-frequency and the opposite direction carrier-frequency. To enable a common repeater to be utilized, audio-carrier separating filters are employed at each repeater station.

*Telephone cables.*—Buried armoured cables, instead of the duct system, are being more generally adopted. In this country, aerial cables will in future be only rarely used. Under suitable conditions the laying of cables has been very considerably expedited by motor-driven trenching and laying machines.

The following submarine and land cables laid recently (see Table 2) have certain features of especial interest:—

TABLE 2.

| Cable | Sheathing, armouring, etc. | Make-up | Length | Conductor weight and loading | Remarks |
|---|---|---|---|---|---|
| Anglo-French (1933) submarine cable (p.c.s.q.).* Laid between St. Margaret's Bay (Kent) and Calais | One lead sheath (99·25 per cent lead, 0·5 per cent antimony, 0·25 per cent cadmium), rubber-covered throughout and armoured | 19 quads, each one screened by metallized paper | 26·31 nauts | Conductors 66½ lb., non-loaded | Average pair-to-pair cross-talk = 122 decibels at audio frequencies |
| Anglo-Belgian (1932) submarine cable (p.c.s.q.).* Laid between St. Margaret's Bay (Kent) and La Panne | Double lead-sheathed and armoured, with only shore sections rubber-covered | 30 quads, with a diametric electrostatic screen | 49·12 nauts | Semi-continuous loading at 0·125-naut intervals. Loaded conductors 21 lb., non-loaded conductors 43 lb. | Average cross-talk between pairs on opposite sides of screen = 128 decibels at audio frequencies |
| Carmarthen – Milford Haven cable (p.c.s.q.)* | Lead-covered: 47 of the 51 miles of the cable are armoured with two layers of mild-steel tape | 38 pairs | 51·0 miles | Loaded with 30-mH buried coils at 2 000-yard spacing for audio and carrier working | |
| Derby–Leeds (No. 2) cable (p.c.s.q.)* | Lead-covered (non-armoured) | 542 pairs | 74·0 miles | 20-lb. conductors loaded with 88-mH coils at 2 000-yard spacing | The largest trunk cable in the British Isles |

* Paper-core star quad.

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* Höpfner: "Tests with Two-Band Telephony on the No. 8 German-Swedish Submarine Telephone Cable," *Europaischer Fernsprechdienst*, 1929, No. 14, p. 229.

*Location of submarine-cable earth faults by means of electrodes.**—A new method has been developed for locating the line of a faulty submarine cable and the position of an earth fault thereon. The method is different from existing fault-location tests in that it is used from the ship itself.

An earthed a.c. supply of 17 cycles per sec. is fed into the faulty core from one end of the cable. The leakage current returning from the fault via the sea produces a voltage gradient in the water between the fault and the 17-cycle machine earth. This voltage gradient is of the order of a few microvolts per yard. Two electrodes are towed from the ship, the distance between them being approximately 20 yards. Each is connected by an insulated lead to a highly sensitive tuned amplifier-rectifier, which, as at present developed, will give sufficient output from 10 microvolts of input to cause a deflection of 100° on a unipivot galvanometer. It will be seen, therefore, that if the electrodes are towed in such a way that they lie in the direction of the voltage gradient, very definite indications will be given on the galvanometer. These indications are at a maximum when the electrodes are over and parallel to the cable and between the fault and the 17-cycle machine. Beyond the fault the indications fall rapidly to zero.

This method has been used successfully in many cases during the last 2 years, notably on four North Sea cables in June of this year. In the case of old cables which are heavily sanded and are thus difficult to hook, much grappling time is saved if the cable line can actually be determined, instead of it being necessary to place reliance on the accuracy of its charted position and a dead reckoning.

*Routine transmission testing.*—For some years past the technical possibilities of carrying out routine tests of the transmission efficiency of telephone circuits and subscribers' apparatus by the simplest means capable of giving reliable quantitative results has been under consideration by various administrations. Satisfactory methods have been in use for some years for routine measurements of levels, attenuations, and gains, on trunk telephone circuits, but transmission measurements of the local and junction network and subscribers' apparatus have been a considerably more difficult problem. The British telephone system has now reached a solution of the problem, and Great Britain is believed to be the first country to introduce a comprehensive testing scheme. A brief description of this scheme will now be given.

Three pieces of apparatus are used: (1) an oscillator, (2) a decibel-meter, (3) a constant-volume sound generator. (1) The oscillator is small, light, portable, and produces current at a constant level at frequencies of 300, 800, and 2 000 cycles per sec. The oscillator is fed from telephone-exchange batteries of any voltage. (2) The decibel-meter in its portable form is small enough to go into a maintenance man's tool kit and consists of a moving-coil milliammeter and a cuprous-oxide rectifier; this meter, when used in conjunction with the oscillator, gives direct readings in decibels, in which the scale is calibrated. (3) The noise generator is a small clockwork-driven device measuring $2\frac{13}{16}$ in. × $2\frac{13}{16}$ in. × $2\frac{1}{4}$ in. and weighing 1 lb. It is arranged to give a rhythmically-varying sound with a field strength somewhat above that of normal speech, when the apparatus is placed against the subscriber's transmitter mouthpiece. When the subscriber's line is connected at the telephone exchange to a decibel-meter, and the noise generator is put into operation at the subscriber's office, the decibel-meter deflection gives an indication of the transmission efficiency of the combination of the subscriber's transmitter and his local line. The oscillator, in conjunction with the decibel-meter, enables the attenuation of lines and exchange apparatus to be measured. It is not proposed at present to make measurements of the subscriber's reception.

*Automatization of British telephone system.*—The automatization of the telephone system has progressed considerably during the past 3 years. At the beginning of this period there were 580 automatic and 4 306 manual telephone exchanges in operation, with 511 042 and 1 442 788 stations respectively. There are now 1 504 automatic and 3 901 manual exchanges serving 851 666 and 1 345 650 stations respectively. The number of rural automatic exchanges has increased from 360 to 1 139.

Practically all local exchanges now being installed are automatic, since the art of automatic telephony has reached the stage at which the manual telephone exchange, except in rare instances, is no longer an economic proposition, irrespective of size.

A number of new automatic systems incorporating features of considerable value have appeared during the last 3 years. Some of the features of these new systems have been incorporated in the British standard automatic system, notably the use of 200-point line-finders and the re-routing facility for director areas. By the latter arrangement, calls which find all direct junctions busy can be re-routed via the tandem exchange. Considerable economy in junction provision is thus obtained.

In the London area 4-frequency voice-frequency key-sending has been extended to 7-digit key-sending. By this means traffic from manual exchanges is routed via a convenient automatic exchange, and from there to the required exchange, which may be either automatic or manual. In the latter case the call goes through the coder call-indicator equipment. This scheme has eliminated a considerable number of key-sending "B" positions at the tandem exchange.

The automatic exchange for rural areas has received attention, and is standardized in 25-line units up to a maximum of the order of 800 lines. For the case where there are insufficient subscribers in an area to justify the rural automatic exchange unit, an alternative termed a "country satellite" has been designed. This consists of an apparatus unit in a weatherproof box fixed to a pole conveniently situated with respect to the subscribers. The subscribers' lines, up to a maximum of 10, would all be brought to this unit and a junction from it to the parent telephone exchange provided. All the current for the switching unit and the subscribers' telephones would be taken from the parent exchange. The maintenance of this country satellite would be a simple matter for the lineman. In case of a fault he would bring along a new unit, take the faulty one out of the box on the pole, and jack in the new one. This system has, however, not yet been definitely adopted.

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* W. T. Palmer and F. E. A. Manning: "Electrode Testing Methods Applied to Telephone Cables," *Post Office Electrical Engineer's Journal*, 1933, vol. 26, p. 36. S. Hanford and L. Voss: "Electrode Method of Locating an Earth Fault on Submarine Cables, and the Development of Apparatus for Use on Cable Ships," *ibid.*, 1933, vol. 26, p. 180.

The arrangements for the subscribers' group service intended for residential areas are on the same principle as the country satellite, except that intercommunication is not provided. In this group service a maximum of 8 subscribers is connected to 2 pairs of exchange lines.

The junction lines now provided between exchanges in provincial areas usually consist of 10-lb. conductors with amplifiers. Efficient speech transmission is assured by the amplifiers, but signalling over these lines is now the subject of investigation. Automatization of these areas, except for trunk calls, is now possible with automatic registration (multi-metering) and subscriber-to-subscriber dialling; the latter will necessitate voice-frequency methods for dialling.

On the Continent, subscriber-to-subscriber dialling has been considerably developed on medium-distance non-repeatered lines by using 50-cycle current taken from the power mains for dialling. A notable example is the service between Basle and Zurich, which gives full automatic working between subscribers in these two cities.

Trunk exchange equipment now provides convenient methods for timing the duration of a call. This will soon be further facilitated by an automatic time signal which will be given at 3-minute intervals. The calling subscriber will hear four " pips " of tone, similar to the B.B.C. time signal, just before the expiry of each 3 minutes.

Voice-frequency ringing methods, which originated in America and are in universal use on repeatered circuits, are now being superseded by systems giving full signalling and dialling facilities by the aid of voice-frequency currents. The system now under development in this country employs two frequencies, 600 and 750 cycles per sec., and automatic calling and supervisory signals are given. A British manufacturer has installed voice-frequency signalling equipment, using another two-frequency system, on trunk lines in Italy.*

*Interference.*—A considerable amount of experimental work carried out in this country is summarized in the recent paper by Radley and Whitehead.† The work done both in this country and abroad during the past 3 years has been outstanding as regards interference investigations in that it has made it possible to predetermine interference effects quantitatively with much greater precision than heretofore.

Field tests carried out in Germany in connection with the coupling between two parallel lines had given results which had appeared anomalous when compared with the theory of the distribution of an alternating current in the earth. It has now been shown that the results are explainable by stratification of the earth, and theory has been strengthened thereby.

*Amalgamation of telephone and telegraph networks.*—In Great Britain the telegraph network has been taken over by the Telephone Branch, and certain important underground routes are being modernized by the introduction of light loading, repeater stations, and single-channel carrier equipment. These circuits will then all be suitable for telephonic working. Those circuits required for telegraphy will be rented to the Telegraph Branch, and the latter will make use of voice-frequency multichannel telegraphic equipment. Further reference to this will be found under the heading " Telegraphy " (see page 174).

During the past 3 years the permanent buildings of the British Post Office Telecommunication Research Station at Dollis Hill have been brought into operation. The well-equipped laboratories are proving of very considerable value in facilitating technical developments in telecommunication.*

### *International Telephony.*

Despite the effects of the world-wide trade depression, the growth of international telephonic communication has continued to make substantial progress during the period under review. By 1933, the latest date for which figures are available, the number of telephones in the world had reached 32 941 570, and the number of miles of telephone wire 150 323 000.† The number of Anglo-Continental telephone calls has increased from 1 120 066 for the year ending March, 1931, to 1 283 854 for the year ending March, 1934, an increase of 14·6 per cent. The Anglo-Belgian and Anglo-French cables laid in 1932 and 1933 respectively are designed to meet a continuance of this growth. When brought fully into use, the former will provide 60 4-wire circuits and the latter 38 4-wire circuits, using the single-channel 4-wire carrier system previously mentioned.

Among other places in Europe, the long-distance service has been extended during the past 3 years to the following: Corsica, Athens, Istambul (Constantinople), and Leningrad; and, in connection with the European network, to the principal places in Algeria, Tangier, and Tunis.

As regards telephonic communication to countries outside Europe, the following new radio-telephone services have opened since 1931.

*London to Brazil.*—A service was opened in May, 1931, to Rio de Janeiro, using a wavelength of 14·72 m. Extensions were opened to the State of Minas Geraes in November, 1932, and to San Paulo and Santos in January, 1933.

*London to South Africa.*—A service to Cape Town was opened in February, 1932, and was extended to Johannesburg and Pretoria in August, 1932, and shortly afterwards to Bloemfontein, Kimberley, and Durban. Extensions to Pietermaritzburg were available in November, 1932, and to the major towns in Northern and Southern Rhodesia in December, 1933. The wavelength used on this service is 15·81 m.

*London to Egypt.*—This service is operated on wavelengths of 22·08 and 27·85 m. The circuit was opened to Cairo and Alexandria in June, 1932, and was extended to Port Said, Assuan, and Luxor, by the end of that year. Extensions to other major towns were available by June,

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* T. S. Skillman: "Developments in Long-Distance Telephone Switching," *Journal I.E.E.*, 1934, vol. 75, p. 545.

† W. G. Radley and S. Whitehead: "Recent Investigations on Telephone Interference," *ibid.*, 1934, vol. 74, p. 201.

* B. S. Cohen: "Research in the British Post Office," *Journal I.E.E.*, 1934, vol. 75, p. 133.

† "Telephone and Telegraph Statistics of the World, Jan. 1st, 1933," published by the American Telephone and Telegraph Co., 1934.

1934. In the same month this service was extended to the major towns in Palestine, i.e. Jerusalem, Haifa, Jaffa, Gaza, Tel-aviv, Bethlehem, and Jericho, and by October, 1934, to all parts of Palestine. The Egyptian service was also extended to Beirut (Syria) in November 1934.

*London to Canada.*—In July, 1932, a direct service to Canada was opened from Great Britain. Calls from the British Colonies are relayed via the direct link, other countries being extended to Canada via New York. The Canadian service is operated on 16·63, 22·08, 32·33, and 69·44 m.

*London to New Zealand.*—This service was opened via the Australian circuit in July, 1932, and can be extended to all towns in New Zealand. The operating wavelength is 27·85 m.

*London to India.*—This service was opened in May, 1933, using wavelengths of 16·11 and 30·15 m. Extensions were available to Poona and Bombay. In June, 1933, the service was extended to Akola, Amrooti, Indore, Nagpur, Calcutta, etc., and, before the middle of 1934, to the principal towns in the Province of Punjab, North-West Frontier, United Provinces, Bihar, and Bombay Province.

Telephone conversation can now be effected with certain liners during their voyages, and new services to Japan, Shanghai, Kenya, and Iceland, are projected.

As a result of the extension of international telephonic facilities, the percentage of the world telephone subscribers who can now intercommunicate has increased to about 95, and it is of interest to note that the subscribers in this country can speak to such far-distant cities as Honolulu, Wellington (New Zealand), Perth (West Australia), Bangkok, Johannesburg, and Santiago.

### *Foreign Technical Developments in Long-Distance Telephony.*

In Germany the *zweiband* system previously referred to has been used on certain submarine cables in the Baltic. For land cables[*] a single-channel 4-wire system has been introduced and is already in service between Berlin and Hanover.

In the U.S.A. very striking developments are foreshadowed.[†] The American Telephone and Telegraph Co. have developed, and are preparing to utilize, a system employing single-pair concentric-conductor cables capable of transmitting up to 1 megacycle per sec. It is proposed to operate up to 200 carrier channels, each of 5 000-cycle band width, on such a cable, with unattended repeater stations at about 10-mile intervals. A system such as this is rendered possible by (*a*) the use of the Black repeater, a negative reaction amplifier which gives entire freedom from cross-modulation between carrier channels, and stability of gain with considerable variation in power supply; and (*b*) the use of quartz-crystal filters, which, in conjunction with double modulation, render separation of 5 000-cycle bands over a range of 1 million cycles per sec. economically possible. It is probable that, but for the depression (which has reacted on the telephone service in America to a greater extent than in any other country), this new system of multi-channel working would have been already in service.

### *The Work of the International Consultative Committee on Long-Distance Telephony.*

The striking advances in long-distance telephony have been assisted to a very material extent by the co-ordinating work of the C.C.I.F. During the period under review the technical committees of this body have met four times, and their work has been formally approved at plenary meetings held in Paris, Madrid, and Budapest.

A few of the more important points on which agreement has been reached and recommendations formulated are: (1) Specifications for international broadcast circuits. (2) Formation of a committee in connection with the maintenance of international circuits. (3) Revision of specifications (22 in number) relating to the provision and maintenance of international circuits, and formulation of two further specifications in connection with 2-channel carrier systems and submarine cables respectively. (4) Certain factors leading to the improvement of international circuits, such as reduction of the transmission equivalent of international lines to zero, extension of frequency-band transmitted, and limitation of permissible line noise to an agreed maximum. (5) Reservation of circuits of high propagation speed for inter-continental traffic. (6) Facilities for the use of international circuits for telex—a carrier frequency of 1 500 cycles per sec. has been provisionally suggested.

It is of interest to note that the number of countries represented on the International Consultative Committee is now 38, including Japan and China.

## TELEGRAPHY.

The period under review has been one of very considerable activity in the British Post Office in regard to the reorganization of telegraph methods and introduction of new facilities. The reorganization of the inland telegraph service has been described as the most revolutionary change in the telegraph history of this country. The teleprinter has now effectively replaced all other telegraph systems in the inland service, and the scope of phonogram and telephone-telegram working has been extended with the introduction of improved switchboard equipment and the provision of typewriters for the direct typing by the receiving operator of messages dictated over the telephone. At the same time the lay-out of the instrument rooms has been improved by removing from the instrument tables all apparatus not actually required by the operators, and concentrating it on vertical racks. Band conveyors have been provided to facilitate the internal circulation of messages. The effect of these innovations has been to give an improved operator output, to speed up the transmission of telegrams, and to give greater stability of working. Further changes of far-reaching importance will now be dealt with at greater length.

### *Multi-Channel Voice-Frequency Working.*

Under this scheme almost the whole of the telegraph-cable network formerly used to provide direct-current telegraph circuits is being released and will be adapted to carry telephone circuits. Reference to this has already been made in the section dealing with telephony. This change has enabled large numbers of telegraph channels to be economically provided and at the same time facilitated the extension of the telephone trunk services to meet the increase of traffic since the introduction of "on demand" working. At the present time there are working 50 multi-channel systems, giving 742 channels. The multi-channel system adopted was developed and manufactured in Great Britain.* Up to 18 duplex telegraph channels can be worked on one 4-wire telephone trunk at speeds approaching 80 bauds. The carrier frequencies used are all odd multiples of 60 cycles per sec., the lowest frequency being 420 cycles per sec., and in an 18-channel system the highest is 2 460 cycles per sec. The choice of odd multiples of a basic frequency has the advantage that even harmonics, produced on account of non-linear characteristics of the transmission link, lie in the regions midway between the carrier frequencies, so that the most advantageous discrimination against the unwanted frequencies is given by the channel filters. The 18 frequencies are all derived from a single multi-frequency generator, one generator being capable of supplying the necessary output for ten systems. The telephone circuits over which the systems are worked are normally maintained to be within ± 2 decibels of the specified overall transmission equivalent, but the system is designed so that variations of ± 8 decibels may occur without appreciable detriment to the working.

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[*] K. DOHMEN and H. F. MEYER: "Carrier Frequency Systems for Trunk Cable Circuits," *Europaischer Fernsprechdienst*, 1934, No. 34, p. 11.

[†] L. ESPENSCHIED and M. E. STRIEBY: "Wide Band Transmission over Co-Axial lines," *Electrical Engineering*, 1934, vol. 53, p. 1371.

The introduction of multi-channel voice-frequency working and the use of what are known as "by-product" circuits has greatly facilitated the supply of telegraph channels, and these are being offered to the public as private telegraph circuits at favourable rentals. This service is proving to be popular; over 200 such circuits are now in use, and there is a steady increase in the demand. The "by-product" circuits are unloaded phantom and double-phantom circuits in telephone cables, not suitable for telephone purposes, and are worked as direct-current telegraph circuits. The inclusion of a simple low-pass filter in the telegraph circuit adequately removes all trace of telegraphic interference in the telephone circuits.

### *Telex (Telegraph Exchange) Service.*

This service, in which a subscriber is supplied with a teleprinter and can then exchange typewritten communications with any other subscriber similarly equipped, has also been introduced during the period under review. There are at present nearly 200 installations. The service is available at most of the larger centres in Great Britain, and includes a "printergram" facility whereby the subscriber has direct communication with a telegraph office for the transmission and reception of telegrams by teleprinter, with a considerable reduction of delay. An average number of over 8 000 telegrams per week is being handled at the London printergram positions in connection with this service.

The telex service has been provided on the ordinary telephone network. Communication is established by telephone in the ordinary way, the subscriber then going over to teleprinter by throwing a switch. Teleprinter signalling is by means of a 300-cycle carrier tone. The equipment to enable voice-frequency working to be carried out consists of a compact unit containing an oscillating valve and three receiving valves, worked directly from the electric mains. The unit is designed to work satisfactorily without adjustment over a connection having any transmission equivalent up to 30 decibels, and direct operation of the teleprinter is secured without the intervention of any electromechanical relays. The equipment is also being used to give renters an alternative telephone-teleprinter service on telephone private wires.

### *Regenerative Repeater for Teleprinter Systems.*

In telegraphy a regenerative repeater receives signals which have been distorted in the transmission link, and reconstructs them so that they may be retransmitted essentially free from distortion. It is thus possible to work over considerably longer lengths of line than with ordinary non-regenerative repeaters.

Telegraph cable companies have for many years used at the end of long submarine cables synchronous regenerative repeaters of a complicated and expensive character. Such elaborate methods are not justified in land telegraphy, where shorter links and retransmission are less costly. Over the longest land cable-links and certain circuits, however, signals may become so distorted that working is uncertain or impracticable. The extensive network of telephone cables now existing provides many circuits or links, which, when joined in tandem to form a long circuit, either permanently or by switching, with normal repeaters, may be unworkable on account of the great amount of distortion produced. The interpolation of one or more regenerative repeaters would enable such a circuit to be used. An interesting form of regenerative repeater has been designed by Jolley for teleprinter circuits. The main feature of this start-stop regenerative repeater is that there is no storage of the received signal, and this has enabled the device to be made in a simple form.*

An important general development has been the introduction of a technique for the measurement of telegraph-signal distortion and apparatus margin, and the production of instruments for making the necessary measurements.†

### *International Telegraphy.*

The technical possibilities of international teleprinter service over the telephone network are being investigated by a joint committee of the C.C.I. Telegraphs and C.C.I. Telephones. In this connection it is of interest to note than an experimental ultra-acoustic teleprinter channel between London and Rotterdam has been tested. A frequency of 2 900 cycles per sec. was used for both "go" and "return" channels, and the circuit was superposed on telephone circuits in the Aldeburgh–

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* J. A. H. Lloyd, W. N. Roseway, V. J. Terry, and A. W. Montgomery: "A New Voice Frequency Telegraph System," *Electrical Communication*, 1932, vol. 10, p. 184.

* E. H. Jolley and J. A. S. Martin: "Regenerative Repeater for Teleprinter Systems," *Post Office Electrical Engineer's Journal*, 1933, vol. 26, p. 171.

† E. H. Jolley: "Determining the Transmission Efficiency of Telegraph Circuits," *ibid.*, 1933, vol. 26, p. 1.

Domburg No. 3 cable. The experimental tests proved very successful, and arrangements are being made for a practical trial of the channel under traffic conditions.

The channel has since proved satisfactory in traffic, and it is proposed to set up two permanent circuits early in 1935. The carrier frequency will probably be 2 940 cycles per sec., as this is the C.C.I.T. figure. The units for the experimental trials were developed and supplied by the Dutch administration.

The cable companies have improved the design and extended the use of their own types of regenerative repeaters, so that there is now no limit to the number of intermediate repeaters. For example, direct cable circuits between London and Australia, China, South Africa, and North and South America, are now regularly working. The successful working of such circuits, with as many as 14 intermediate stations, requires the greatest possible stability of the relaying apparatus.

There is a tendency on the North Atlantic cables to extend to non-loaded cables the use of the 5-unit code system so far mainly confined to loaded cables, and there has been considerable development generally of faster working on long cables by the use of higher channel speeds and storage transmitters, the latter eliminating the drag inherent in the use of perforated slip.

" Channel " working is now a common practice, some cables being worked permanently in this way, and some when emergencies demand. By this system the signals of two channels pass through the cable in rotation alternately; such a system is basically, of course, that of Baudot, the separation being a question of appreciation of " time," involving synchronism, and not a matter of frequency selection.

The advantages of the system have been increased by the perfection of adjuncts to the regenerators, these adjuncts being variously known as interpolators, channel repeaters, combiners, and sending and receiving channel assigners. Their function is to separate signals from a " channelled " cable for relaying to two or more connecting cables, or vice versa. These devices are working successfully with both cable, Morse, and 5-unit code, and in the latter case the necessity for synchronism between the stations of one section and those of the next has been eliminated.

An interesting development for landline working is an 8-frequency carrier system on one pair, each frequency giving three duplex multiplex channels in addition to three similar channels on each wire. This scheme is working between New York and Buffalo.

### *Picture Telegraphy.*

There has been a considerable extension of the picture telegraphy service since the date of the last review. The following additional cities are now equipped for this service: Oslo, Rome, Amsterdam, Paris, Strasbourg, Marseilles, Lyons, Nice, and Toulouse. There are, in addition, private newspaper services to Berlin, Paris, and Turin. All of these offices use either the Siemens–Carolus system or the Belin system, and intercommunication can be made between any of them. A public service is operated between Sweden, Norway, Austria, Germany, Denmark, Italy, and America, via London; and also between London and New York, and London and Australia. A poorer-quality " black and white " public service system is also working between Amsterdam and Bandoeng, and between Berlin and Buenos Ayres and New York. Another development has been the production of portable picture transmission sets, which are being used to a considerable extent in Great Britain and France. These can be used over any good-quality line to transmit to one of the fixed stations.

## ACKNOWLEDGMENT.

The author desires to express his indebtedness to colleagues, both inside and outside the Post Office, who contributed information embodied in this review.

# RADIO-TELEGRAPHY AND RADIO-TELEPHONY.*

By Colonel A. S. ANGWIN, D.S.O., M.C., B.Sc.(Eng.), Member.

## INTERNATIONAL REGULATIONS.

The International Regulations for the Control of Radio Communications have been modified by the Madrid Telecommunications Convention of December, 1932.† The frequency allocations previously in force under the Washington Regulations have been varied. Special allocations of frequency between 160 and 400 kilocycles per sec. have been made for broadcasting services in Europe, and there have also been increased allotments between 225 and 265 kilocycles per sec. Some subdivision of the frequency bands above 4 000 kilocycles per sec. allotted to mobile services has also been made in order to provide separation between coast stations and ship transmitters of stable frequency in one category and ship sets having an uncontrolled frequency transmission liable to vary by ± 0·04 per cent in another. Desirable limits of frequency tolerance for all types of transmitters are specified.

Other clauses in the Madrid regulations have considerable bearing on the broadcasting problem. An Article of the Radio Regulations of a general character which permitted Governments to assign any wave to a station on the sole condition that interference with a service of another country was not caused, has in the past given rise to considerable laxity in its interpretation; and it has been considerably strengthened in the new Regulations with a view to making its abuse very much more difficult. The limitation of power of broadcasting stations is also provided for in the Regulations.

The Madrid Convention was followed by a European Governmental Conference at Lucerne in June, 1933, for the purpose of establishing a wave plan among European broadcasting stations. From 1929 to 1934 the broadcasting stations of Europe had been working under the Prague wavelength plan. It became necessary, however, to replace the Prague plan, for many reasons, of which the following are the most important: (1) The considerable growth in the number and in the power of broadcasting stations in Europe. (2) The necessity of taking into account the dispositions of the Madrid Telecommunications Convention, which had changed, in some respects, the bands of wavelengths allotted to broadcasting stations. (3) The enlargement of the European Zone. This latter, as defined at Madrid, includes the U.S.S.R. up to meridian 40° east of Greenwich, Turkey, Syria, Palestine, Egypt, Cyrenaica, Tunis, Algeria, and Morocco down to 30° north. After discussions lasting over six weeks the Lucerne Conference came to a decision which was unfortunately not unanimous. Twenty-seven of the thirty-four nations represented signed the Convention. The non-signatories were mainly dissatisfied with the long-wave band allocation, and it was practically possible to put the medium-wave part of the Lucerne plan into force on the 15th January, 1934. After some weeks of relative chaos in the long-wave band the International Broadcasting Union succeeded, in March, 1934, in securing the adoption of a *modus vivendi* which has now been almost completely applied, with a considerable improvement in the situation. The situation is complicated, however, by the presence in the long-wave band of two stations—Luxembourg and Madona (Latvia)—which were not provided for in the Lucerne Plan, and by the new stations projected for Madrid, Ankara, and Brasov (Rumania). A respite of one or two years, has, however, been achieved.

A meeting of the Comité Consultatif International Technique des Communications Radioélectriques (C.C.I.R.)† held at Lisbon in September–October, 1934, has followed these conferences and deals with the technical aspect of these international regulations. *Avis* were issued on many questions, including selectivity and stability of receiving apparatus, intensity of harmonic radiation from transmitting equipments, radiotelephony between boats of small tonnage and coast stations, wave propagation, and the use of the carrier and single side-band system for broadcast transmissions.

## BROADCASTING.

The general development of broadcasting in Europe during the past two years is best illustrated by the increase in the number of licensed listeners. The total in Europe for those countries for which reliable statistics are available was 13 678 330 at the beginning of 1932, whereas at the end of March, 1934, the total was 19 626 315. This large increase is due in no small measure to the considerable technical progress which has been made in the past. The increases in the number and size of European broadcasting stations are as follows:—

| | 1929 Prague Plan | 1934 Lucerne Plan | 1934 projected |
|---|---|---|---|
| Number of European stations | 200 | 254 | 270 |
| Total power, kW .. .. | 420 | 4 300 | 6 500 |
| Maximum power, kW .. | 40 | 500 | 500 |
| Mean power, kW .. .. | 2·1 | 17 | 24 |

The maximum power of broadcasting stations in Europe as provided for in the Madrid regulations is limited to 100 kW in the medium-wave band (200–500 m), and to 150 kW in the long-wave band (1 000–

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* A review of progress.

† General Radio Communications Regulations, Madrid, 1932 (H.M. Stationery Office).

† Questions of C.C.I.R. Reunion, Lisbon 1934 (Bureau of International Union for Telecommunications, Berne).

2 000 m), with the exception of one station at Moscow which has a power of 500 kW.

The scheme of broadcast distribution in this country has progressed according to plan. The Scottish Regional transmitting station at Westerglen, near Falkirk, and the West Regional transmitting station at Washford Cross, near Watchet, Somerset, have both been completed; the former entered into dual-programme service on the 25th September, 1932, and the latter on the 13th August, 1933. With the opening of the latter twin-wave station the original "regional scheme" of five twin-wave stations was completed. It was subsequently decided to supplement the original scheme by replacing the low-power transmitter situated in Belfast by a high-power transmitter capable of serving most of Northern Ireland. A site has been selected for this transmitter, which is at present in course of construction.

*Synchronization of Broadcast Transmitters.*

With the opening of the National programme transmitter at the West Regional transmitting station, the B.B.C. was faced with the interesting problem of synchronizing two high-power transmitters. The international wavelength situation did not permit of sufficient wavelengths being allotted to Great Britain to allow these two transmitters to use separate wavelengths. It is now well known that if two transmitters work on the same wavelength, each transmitter will give good service in an area immediately surrounding it, but there will be an area in between the two stations where uninterrupted reception of either transmitter will not be possible. In this country seven low-power transmitters have been worked on one wavelength and satisfactory operation obtained, each transmitter being driven by a separate tuning fork with thermostatic control of temperature. In practice it was found possible to maintain the frequency of the seven stations with an accuracy of about 1 part in 100 000. Experience with these stations confirms the original experiments made in 1927 showing that, when perfect quality is judged on the highest-quality receiver, a ratio of 5 : 1 is necessary between the field of the wanted station and the total field produced by the unwanted station.

For the synchronization of the London and West National transmitters similar frequency-stabilizing apparatus was used. The carrier frequency was 1 147 kilocycles per sec., and it was found possible to keep the beat frequency between the two transmitters to a maximum of 5 cycles per sec., representing an accuracy of 1 part in approximately 200 000. The originally-established field-strength ratio of 5 : 1 was confirmed as necessary under these conditions. The experiment was then tried of driving both transmitters from the same tuning fork, situated at one of the transmitters, the fundamental frequency of the tuning fork (1 122·07 cycles per sec.) being sent to the distant transmitter by telephone line. An examination of the interference pattern produced by the carrier waves of the two transmitters showed that there were phase differences between them; but listening experiments showed that these were of less importance than the original rhythmic variation of the resultant field caused by the frequency-difference between the carriers varying up to 5 cycles per sec. The net result was that the service area of both transmitters was extended, the field-strength limit ratio of 5 : 1 then being reduced to approximately 3 : 1 for high-quality reception. Contemporary experiments both in the United States of America and in Germany gave similar results. It should be emphasized that the above figures hold only when the same programme is transmitted by the synchronized stations.

*New Long-wave Broadcasting Transmitter.*

As a result of the Lucerne Conference the B.B.C. retained the long wavelength in use at Daventry, but it was realized even in 1932 that the best possible use was not being made of this valuable channel by the 7-year-old transmitter at Daventry, radiating only 25 kW. In the case of Daventry 5XX the quality in distant areas was markedly inferior to that given by the modern medium-wave regional stations, and for this reason it was decided to build a new long-wave station with much greater power. Accordingly the erection at Droitwich of a new long-wave transmitter of 150 kW was proceeded with. This transmitter has now been completed; the signal strength which it provides will, it is anticipated, ultimately make unnecessary the relaying of the same programme by a medium-wave transmitter in the London, West, and North regions.

*Studio Design.*

In the previous review* on this subject the question of acoustics of broadcasting studios was dealt with at some length. On this occasion it may be interesting to note that the studios at Broadcasting House, which were taken into use early in 1932, have proved that the conclusions of that report were justified.

The studio accommodation at most of the Regional centres in the provinces has been brought up to date by the provision of studios similar to those at Broadcasting House. New studio premises have been completed at Newcastle, Manchester, Leeds, Birmingham, Cardiff, and Bristol. In London, a large studio for the use of the B.B.C. symphony orchestra of 119 players is in course of construction at Maida Vale. The new studio has been constructed inside a portion of the Maida Vale skating rink. This construction is interesting in that it is an almost separate building inside the existing fabric of a portion of the skating rink. Separate walls and roof trusses have been provided with a view to preventing the transmission of sound through the members of the roof to any further studios which may be constructed in the remainder of the skating rink at a later date. This broadcasting studio is the largest which has yet been built in this country, having a volume of 228 900 cub. ft.

*Broadcast Relays.*

During the period under review considerable progress has been made in the relaying of broadcast programmes over telephone circuits. In addition to the provision for relaying foreign programmes, practically the whole of the internal simultaneous broadcast system has now been changed over from the old overhead open-wire circuits to underground cable circuits. Some 4 000–5 000 miles of underground circuits are permanently rented from the

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* *Journal I.E.E.*, 1932, vol. 70, p. 145.

General Post Office by the B.B.C. for linking up the various stations and Regional headquarters.

The second noteworthy development in the relaying of programmes over great distances has been the increase in the use of radio-telephone circuits for linking up the broadcasting organizations in the various continents. An outstanding example of the use of radio-telephone circuits for the collection of material and the distribution of the finished programmes was provided by the Christmas Day programmes in 1932 and 1933, culminating in His Majesty's message to the Empire.

### *Sound Recording.*

The last two years have seen further developments in the art of sound recording. The steel-tape method of recording, now generally known as the Blattnerphone, has been further developed and the quality of reproduction considerably improved. A new type of Blattnerphone recording machine which is now used is capable of giving a playing time of 30 minutes, and it is found in practice that continuous playing can be obtained by the use of two machines, skill in operation allowing one machine to be changed over to another without any appreciable break in the programme.

### *Short-Wave Broadcasting.*

On the 19th December, 1932, the B.B.C. inaugurated a short-wave broadcasting service from Daventry, intended for reception in the British Empire. Two transmitters, each capable of delivering 15 kW to a number of directional aerials, were provided, and transmissions are made at suitable times on suitable wavelengths in the short-wave bands between 13·9 m and 50 m for reception in the various parts of the Empire. Considerable experience has already been gained on the design of the most suitable aerials for a shortwave broadcasting service of this nature, where the requirements are very different from those for point-to-point services. The original aerials erected at Daventry have now been replaced by others which have proved more suitable in practice, and further developments of the aerial system are still in progress.

### *Anti-fading Aerials.*

With the earlier broadcasting stations of comparatively low power the service area was limited by the distance at which the received signal becomes too much attenuated to override interference. Modern high-power stations, on the other hand, give an adequate signal strength at distances beyond the point where serious fading sets in. The service area is thus determined not by considerations of signal strength but by the radius at which fading becomes intolerable. Fading is due to interference between the directly propagated wave and the wave reflected down again from the ionized layers of the atmosphere. The service area can therefore be increased by the use of aerials whereby the energy radiated at high angles above the horizontal is reduced and the horizontal radiation is correspondingly increased.

It has been shown that, with a single vertical radiating conductor, the horizontal radiated field increases with the height up to the point where the latter is approximately 0·58 of the working wavelength, after which it begins to decrease. On the other hand, the high-angle field decreases with the radiator height until the latter is approximately 0·45 of the working wavelength. The height of radiator which gives the maximum ratio between the directly propagated and the reflected fields at the receiving point is thus a compromise between these two figures, the actual value depending to some extent on the attenuation factor of the surrounding territory and on the wavelength. For average country and on wavelengths between 400 and 500 m a radiator height of about 0·55 of the working wavelength is most satisfactory.

For a radiator of this kind the conventional type of aerial suspended between two masts can no longer be employed, even if the towers are insulated at the base, on account of the reactions which arise from currents induced in the towers. The solution lies in the use of a single mast of special form which itself acts as the radiator. The first vertical radiator of this kind to be erected in Europe is employed in conjunction with a 120-kW broadcasting station at Budapest, working on a wavelength of 549·5 m. The mast has a movable portion at the top permitting the height to be adjusted between 285 and 315 m (1 020 ft.). Its height is thus greater than that of the Eiffel Tower; it is the highest structure in Europe and the tallest mast in the world. This aerial has amply justified its erection in place of the original high "T" aerial, which had a ratio of working wavelength to fundamental wavelength of 0·63, as it has been found that the service area of the station has been materially increased.

In this country the B.B.C. North National transmitter has used a vertical-wire half-wave radiator supported from a triatic between two 500-ft. masts, since its inauguration in March, 1930. Both transmitters at Westerglen and Washford Cross use a special type of aerial designed by the B.B.C., consisting of three wires supported from the top of a 500-ft. mast in the form of an umbrella aerial. While this type of aerial is not theoretically so efficient as the vertical radiator, having a total height of approximately 0·58 times the wavelength in use, it has the advantages of flexibility, ease of construction, and relatively low cost. It has, however, become so important to attempt to improve efficiency of radiation in the horizontal plane that the new transmitter at present under construction at Belfast will use an experimental vertical-mast radiator having an adjustable height in the neighbourhood of 0·58 times the wavelength in use.

### *Electrical Efficiency of Broadcast Transmitters.*

A result of the general increase in the power of broadcasting stations has been to focus attention on the importance of increasing the electrical efficiency of the transmitters. When the average power consumption was between 10 and 100 kW an improvement of a few per cent in the overall efficiency was not a matter of great interest. Now that an average high-power station consumes some 2 million kWh per year, however, the situation is very different and an increase in the hitherto rather poor electrical efficiency has become one of the main desiderata in design. A new system to give larger efficiency has been brought to the practical stage; this is known as the " floating carrier " system.

The basic principle of the floating carrier system consists in transmitting with a more or less constant percentage modulation and varying the amplitude of the carrier wave, from moment to moment, in accordance with the changes in strength of the audio-frequency signal. In the ordinary system of transmission full carrier power is radiated all the time irrespective of the strength of the audio-frequency signal, and the percentage modulation varies from 0 to 100 in accordance with the latter. With a fully "floating" carrier the modulation remains constant at 100 per cent and the carrier amplitude varies between zero and full value. At maximum audio signal, corresponding to 100 per cent modulation with the ordinary type of transmitter, the power consumption of the two systems (neglecting the power used for filament heating, grid bias, and auxiliary equipment) will therefore be equal. At lower signal values, the power consumption of the ordinary transmitter will remain unchanged, while that of the floating carrier transmitter will be directly proportional to the signal amplitude.

For various practical reasons, particularly on account of the effect on receiving sets fitted with automatic volume control, the floating carrier system is normally adjusted in such a way that with no signal the carrier power is not reduced actually to zero but to about one-fourth of the full power. Even so, however, the total saving in energy consumed over a period is very considerable. Trials that have been made with the system adjusted to operate in this way have shown that with the normal type of programme material the average listener is unable to detect whether the carrier is floating or not.

*Transmitter Design.*

Recent advances in the technique of audio-frequency amplification have influenced the design of high-power modulated transmitters. The system of " series modulation " has been introduced in several of the recent installations. The introduction of the Class B push-pull circuit has given an amplifier with an efficiency of about 50 per cent, as compared with some 20 per cent in the case of the Class A amplifier. At the same time the development of special transformers and distortion-compensating circuits has enabled the difficulties of obtaining good transmission quality to be overcome. As compared with a transmitter modulating on one of the preceding stages, the use of a Class B modulator, operating on the final stage, results—under the unmodulated carrier condition—in a saving of about 40 per cent of the total input power.

As the technique of high-power radio engineering advances, the tendency is increasing to follow the practice already established in heavy electrical engineering. The earlier radio transmitters comprised a collection of apparatus set up more or less in the manner of an experimental laboratory. The next step was the adoption of the enclosed unit construction wherein the apparatus is assembled in free standing enclosed units. A further development now being exploited is to follow the practice adopted in high tension power engineering and to build the apparatus into a series of brick or concrete cubicles which form a part of the actual building in which the equipment is housed.

*Receiver Design.*

The superheterodyne type of receiver has superseded the older type of " straight " set owing to the greater ease with which unwanted signals can be filtered out at an intermediate frequency. The new type of multi-electrode valves which are now available, and the improvement in valve performance, have tended to simplify receiver design and to reduce the number of stages of amplification. The better-class sets are now invariably equipped with automatic volume control. Among components, electrolytic condensers and " metallized " resistances are now widely used, and valves of very small dimensions are being produced for use in sets where a minimum of space is of importance, e.g. in motor-car equipments.

## COMMERCIAL SERVICES.

*Marine Communication.*

During recent years there has been a great expansion in the use of short-wave telegraph working with ships, and world-wide working is now of regular occurrence; e.g. whaling boats in the Antarctic and ships in Eastern waters are being worked regularly from the Post Office stations at Burnham and Portishead. At these stations directive aerials have been erected covering all the main shipping routes of the world, resulting in great improvement in operation of the services. The new types of crystal-controlled short-wave transmitters are specially designed for quick wave-changing by means of mechanical switches instead of by manual change of coils. The receivers are of the triple-detection " quick search " type, specially developed by the Post Office for ship work, in which the entire tuning operation is carried out by the movement of one dial.

*Direction-finding.*

It has been found desirable, in order to reduce the possibility of errors in direction-finding and to give a wider arc of reliable bearings, to place the direction-finding aerials remote from the present coast stations. A trial of this arrangement has been made, with very successful results, at Niton radio station, where the Bellini–Tosi loops have been erected at a point approximately 1 mile from the station, the received signals from the loops being conveyed to the goniometer at the station by means of two underground cables terminated by suitable transformers to match the impedance of the arrays to that of the lines. A phantom circuit on these two lines is used for coupling the vertical aerial to the receiver. As a result of the new arrangement the sector over which the bearings are reliable has been doubled, and in consequence of the reduction in the vertical effect a much sharper definition of bearing has been obtained.

Developments in radio " beacon " installations have continued; in one of the later designs, two distinctive notes are emitted over two sectors, one on each side of a silence zone covering approximately 1°. The complete radiating system is swung backwards and forwards through an arc of 6°, and the ship's observer is able to deduce the correct course from the change of note as the beacon swings through the silence zone.

### *Ship Telephony.*

The number of ships to install telephony equipment in order to facilitate communication between passengers and land subscribers has steadily increased. A large number of trawlers are now equipped with a simple and robust type of telephony apparatus which enables them to communicate with the coast stations. These transmitters work on a wavelength of 177 m with a power of about 50 watts. Corresponding equipment has been installed at all coast stations, but in these cases the transmitters are of higher power with inputs ranging from 500 watts to 3 kW. Although the trawler service is usually operated on a phonogram basis, arrangements have been made at Seaforth to test the possibility of extending the ship subscriber to land subscribers through the general telephone network.

### *Long-distance Telephony.*

Additional radio-telephone services have been opened up from this country to South Africa, Egypt, and India, while services to Japan, Shanghai, Kenya, and Iceland, are projected.

By extension to circuits already existing, telephone communication is now possible between this country and most of the South American states via Buenos Ayres and Rio de Janeiro, and also to Bogota, Honolulu–Manila–Guatemala, Panama, Venezuela, Bermuda, Miami, and Costa Rica, via New York. The service to Egypt has been extended by landline circuits to all the most important places in Palestine and Iraq; the service to Cape Town has been extended to North and South Rhodesia; and the Indian service has been extended to practically every important centre in India.

By means of inter-channel linkages in this country it is now possible for telephone subscribers in one part of the world to speak to other subscribers in practically all other important countries of the world; for instance, a subscriber in Sydney can communicate with one in Bulawayo, the circuit being from Sydney to Baldock by radio, Baldock to London and London to Rugby by landline, Rugby to Cape Town by radio, and Cape Town to Bulawayo by landline. Recently a company conference was held between representatives of a firm in Bombay, Sydney, Johannesburg, and London, each representative addressing the conference in turn; while listening points were provided in Paris, New York, Montreal, Calcutta, Melbourne, and Perth (Australia), at which other members of the company were able to hear all the conversations.

Owing to the decline in solar activity the necessity of utilizing longer wavelengths on long-distance telephony services has been maintained. As an example, on the transatlantic circuits during the past year, wavelengths of the order of 60–70 m have been used during the night periods and 20–24 m during the daylight, as compared with 32 and 16 m used during corresponding periods 5 years ago. The " peak " has now been passed, and it is anticipated that the optimum wavelengths will decrease during the next 5 years. The last 2 years have been remarkably free from magnetic storms.

### *Aerial Systems for Short-wave Communications.*

Considerable use has been made of an improved form of " horizontal diamond " directional aerial. The advantage claimed for this type of aerial is its use for effective transmission and reception over a 3 : 1 wavelength range without the necessity of any adjustment. It can be supported on poles about 60 ft. high and will give a gain of about 15 decibels as compared with a standard dipole.

Another type of aerial, termed the " series phase " aerial, consisting of a number of vertical radiating elements and designed to propagate maximum energy in the plane of orientation, has been developed to meet the demand for a reasonably efficient directional aerial at low cost.

### *Single Side-Band System and Suppressed Carrier Operation on Short Wavelengths.*

Further tests with the single side-band system of transmission have been conducted by the Post Office in conjunction with the Bell Laboratories in New York, utilizing one of the transatlantic channels. These tests have provided considerable data on the merits of the system as compared with the normal double side-band type of transmission, and the application of the system to commercial working is under consideration.

Quiescent carrier operation is now employed on the telephone service between this country and Australia, and is being tried out on transatlantic circuits. With this system no carrier is radiated under " no speech " conditions, a heavy negative bias being applied to the grids of the valves in one of the early high-frequency amplifiers. On the arrival of the speech voltages at the transmitter the carrier is immediately replaced by the operation of sensitive thermionic relays, the interval between the commencement of speech and the application of the carrier being negligible. A considerable saving in power is effected with this system in comparison with the normal method of operation wherein the carrier wave is continuously radiated, and an increased measure of privacy is secured.

### *" Compandor " Equipment.*

This apparatus has been developed by the American Telegraph and Telephone Co. It comprises a " Compressor " unit at the transmitting end of the circuit and an " Expandor " unit at the receiving end of the circuit. The Compressor unit consists of a special " square-root " detector and amplifier, which reduces the range of the amplitudes of the signals delivered to the transmitter. At the receiving end the Expandor apparatus employs a detector operating on the square-law principle which restores the signal to its original form.

Equipments of this type have been fitted at the London and New York terminals of the long-wave transatlantic telephone circuit, and by their use an improvement of 10 decibels in the average signal/noise ratio has been obtained. With this improvement it is possible, during that period of the year when disturbances due to atmospherics on the long-wave circuit are low, to dispense with the final 300-kW stage of the transmitter and to utilize an output stage of 30 kW. It is thus possible to obtain considerable economy in power over a period of about 8 months of the year.

### *High-Tension Supply for Radio Transmitters.*

Recent years have shown a greater tendency towards the use of mercury-arc rectifiers for the h.t. supplies of transmitters, since such rectifiers have a high efficiency and excellent regulation. In addition to the steel-tank type, the glass-bulb type has now been developed to operate at the high voltages required for radio-transmission work. The application of grid control to the arc type of rectifier is a notable development from the aspect of overloads in the transmitter, since the d.c. supply from the arc can be completely cut off—by the application of a negative bias to the control grid—in a small fraction of a second.

Mercury-vapour hot-cathode rectifiers have reached a much greater degree of reliability as regards "flash-back" troubles, and single bulbs of this type are now available, capable of delivering 30 kW at 20 kV. These, and the mercury arc, are fast replacing the less efficient water-cooled diode rectifiers.

### *Transmitting Valves.*

Following on the lines of the successful 100-kW sealed-off valve, a similar valve has been introduced which is rated at 500 kW with a working anode voltage of 18–20 kV. The filament current for a valve of this type is 460 amperes at 30 volts. Valves rated at 100 kW have also been developed for short-wave working.

Demountable valves for use on short-wave transmitting equipments have been further developed, and 30-kW valves of this type are in regular use.

To meet the growing demands for higher-power equipments on ultra-short wavelengths, water-cooled valves have now been produced which operate satisfactorily down to wavelengths of about 1·5 m; while the "magnetron" type of valve has been developed to give a power output of 150 watts.

### *Ultra-short Waves.*

A 2-way commercial link working on wavelengths of 4·5 and 5 m has been in successful operation for some time between Cardiff and Weston-super-Mare, while a 6-circuit experimental channel has been tested between Bristol and Cardiff.

A 9-channel carrier equipment, operating on a wavelength of 8 m, has been experimentally tested across the Straits of Dover—a distance of 30 miles.

The installation is now proceeding of a multi-circuit ultra-short-wave radio equipment for operation between Belfast and Stranraer; when completed, this will form a part of the Scotland–Ireland telephone trunk system.

Wavelengths below 1 m are being increasingly exploited. A "micro-ray" link designed for teleprinter or telephony working on a wavelength of 17·4 cm, with terminals at Lympe aerodrome in Kent and at the St. Inglevert aerodrome in France, spanning a distance of 35 miles, was brought into operation early in 1934 for inter-aerodrome control of cross-Channel flights.

## DEVELOPMENTS IN AIRCRAFT WIRELESS.

### *Use of Short Waves for Aircraft Communication on Empire Routes.*

When the Imperial air route to South Africa was inaugurated it became apparent that atmospheric interference on medium waves would be a serious obstacle to reliable communication on these wavelengths. An investigation was undertaken to explore the usefulness of short waves as a substitute for, or as an alternative to, the 900-m band. As a result of flight tests over various sections of the route covering a period of about 6 months, it was found that a wavelength of 45 m could be employed with advantage. During periods of severe atmospheric disturbances on medium waves a considerable degree of immunity was provided by the use of a short wave. Skip effects on the wavelength of 45 m were observed, but to no serious extent. Medium waves can, however, be used for a fair proportion of the time and are necessary for direction-finding services. The solution arrived at, therefore, was the development of a combined medium- and short-wave transmitter and receiver, and this has been standardized.

### *Directional Aids.*

*Visual beacon.*—The performance of the visual-type equi-signal beacon (which was in course of construction for the Air Ministry at the time of the last review)* has been carefully investigated by flight test and ground observation. The course width, range, and general reliability, have been satisfactorily checked. Distinct indications of a local kink or bend in the course were discovered in the neighbourhood of Sevenoaks with the course directed on Dungeness from Croydon. The Air Ministry Report on the Progress of Civil Aviation for 1933 states: "The tests on this beacon referred to in the last report have confirmed that apparatus of this kind is capable of providing an accurate means for guiding aircraft into an aerodrome from a range of over 70 miles."

*"Homing" apparatus.*—Suitable homing apparatus has been developed to meet the need for a simple direction-finding aid whereby the pilot may be enabled to point the nose of the aeroplane towards the source of any wireless transmission within range. This system has a direct application on the Empire routes and is now in general use. It is referred to as follows in the above-mentioned Report on the Progress of Civil Aviation: "Increasing use has been made by Imperial Airways, Ltd., of the 'wing coil' method of wireless-telegraph direction-finding whereby aircraft are enabled to 'home' on wireless-telegraph stations situated along the Imperial Air Routes. The system has the advantage of requiring little additional equipment in the aircraft, as well as being simple to operate by the crew. No elaborate ground organization is required in connection with this method, as the wireless-telegraph stations required in any case for normal communication purposes only are utilized. In particular, the wing coil method is being used with success on the African route and was found of very valuable assistance on the Australian Survey flight of the 'Astraea.'"

*Marconi–Adcock direction-finder.*—This system of direction-finding, which renders possible accurate direction-finding work by night, has been under continuous trial throughout the period under review. The first installation for the Air Ministry has been made at Pulham, which is one of the two satellite direction-finding stations of the London Terminal Aerodrome. Similar equipment has also been installed for various aerodromes in this country, Europe, the Near East, and India.

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* *Loc. cit.*

## RESEARCH.

Very definite advances have been made in radio research and its application to wireless telephony and telegraphy, both in the laboratories of the manufacturing interests and under the auspices of the Radio Research Board.* The following are some of the principle directions in which research has been directed.

### *Propagation of Waves.*

The outstanding feature has been the intensive study of the ionosphere, particularly in the application of the cathode-ray oscillograph and the adaptation of spaced aerial systems to the study of propagation phenomena. The methods now in use have given increasing evidence that the reflected signal resulting from a single pulse incident on the ionosphere consists frequently of a doublet whose components are separated by a small time-interval, and indicates that these two components are two electrically polarized waves of opposite rotational sense into which the incident wave is split by magneto-ionic double reflection.

A considerable advance has been made with regard to the determination of the optimum angle of propagation in a vertical plane from transmitting aerials on any particular service.† This is usually found, on long-distance services, to lie between 10° and 13° to the horizontal; but it is now customary, in new services, to determine this optimum angle experimentally before embarking on the design of an actual array.

Attempts at correlation of the measured angles with the conditions in the ionosphere, and the resolution of the received signal into its component rays, have been made on a fairly wide range of frequencies from commercial stations in Europe and America.

A valuable summary of the propagation characteristics over a wide range of radio frequencies is contained in the proceedings of the Lisbon conference of the C.C.I.R.

### *Direction-finding.*

Progress has been made in the application of different methods of applying the spaced-aerial or Adcock system of direction-finding in order to produce a direction-finder free from variable errors. The cathode-ray oscillograph is being used with a spaced aerial system, and the application is being extended from the medium-wave to the short-wave part of the spectrum.

### *Cathode-ray Oscillograph.*

The production of a low- and medium-voltage sealed-off oscillograph of greatly improved design has led to its application to many purposes associated with the radio art. Amongst these may be instanced its application to recording photographically atmospherics lasting only 0·002 sec. and also indicating at the same time the direction from which they have arrived.

The cathode-ray oscillograph is also used in investigations on the reflection of waves; it records simultaneously the traces of wireless signals emitted in the form of recurring brief pulses of current received along the ground from the transmitting station and of echoes of the signals received after reflection at the upper atmosphere. The response of the oscillograph is so rapid that it separates the echoes even though the time-interval may be less than 0·0003 sec.

Amongst practical applications of the oscillograph may be cited its use as a direction-finder in a compact and inexpensive form, and as a collision-preventer in fog.

### *Radio-frequency Standards.*

Corresponding to the increased requirements for stability and accuracy of frequency for radio transmission purposes the measurement of radio frequencies has been brought to a still higher standard of accuracy. The results of international measurements on standard emissions generated at the National Physical Laboratory show that international agreement as regards frequency standards can be attained to a few parts in 100 millions, and comparisons of a research character can be made to a few parts in 1 000 millions. The improvements in frequency stability on short waves have a direct bearing on new systems of radio transmissions such as the single sideband suppressed carrier system, where the carrier has to be inserted at the receiving end and the inserted frequency must be within a few cycles per sec. of that of the original carrier.

An interesting development is the production of quartz crystal plates having a zero temperature/frequency coefficient, which render unnecessary the use of auxiliary ovens and thermostatic control of temperature.

### *Television.*

Television has chiefly advanced in the direction of increasing the definition and of exploiting the ultra-short waves for this purpose in order to obtain the wide bandwidth required. Several new systems have been introduced experimentally, and the cathode-ray tube has been developed and applied both for the production of the image at the receiver and as a means of scanning at the transmitter. Interesting papers on this subject have been published in the *Journal*.* Ultra-short-wave transmitters suitable for television have been developed for powers up to 9 kW and with uniform frequency/response characteristics up to 600 000 kilocycles per sec. The possible lines of development of television in this country are dealt with in the report of the Television Committee appointed by the Postmaster-General.

### *Union Radio-Scientifique Internationale.*

A Plenary Congress of this Union was held in London in September, 1934, at which international radio research undertaken since the last General Meeting at Copenhagen was reviewed, and a programme of further work was arranged. In connection with the development of radio-frequency standards, arrangements were proposed for the further extension of international comparisons of the standard of frequency.

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* Report of the Radio Research Board for 1932–33 (H.M. Stationery Office).

† T. WALMSLEY: "An Investigation into the Factors Controlling the Economic Design of Beam Arrays," *Journal I.E.E.*, 1934, vol. 74, p. 543.

* V. K. ZWORYKIN: "Television with Cathode-ray Tubes," *Journal I.E.E.*, 1933, vol. 73, p. 437; and discussion, 1934, vol. 74, p. 276; L. H. BEDFORD and O. S. PUCKLE: "A Velocity-Modulation Television System," *ibid.*, 1934, vol. 75 p. 63.

The further study of methods of measuring field intensity at radio frequencies was proposed, and an accuracy to be arrived at in the standard apparatus has been specified for the frequency ranges below 150 kilocycles per sec. to above 30 000 kilocycles per sec. For the upper and lower ranges, the frequencies suggested are—

| Frequency | Minimum field | Accuracy at minimum field | Maximum field | Accuracy at maximum field |
|---|---|---|---|---|
| kc/s | μV/m | per cent | μV/m | per cent |
| Below 150 .. | 1·0 | ± 5 | $10^6$ | ± 1 |
| Above 30 000 .. | 10 | ± 20 | $10^5$ | ± 10 |

The relations between magnetic activity and abnormal radio phenomena, the theory of propagation and absorption of waves in the atmosphere, ionospheric measurement, the co-relation of solar phenomena and radio transmission, were amongst other subjects reviewed at this Congress.

Valuable work has been done on the subject of the origin and propagation of atmospherics and their energy spectrum. The summary of observations indicates that the effect of propagation of atmospherics in a dispersive medium results in different group velocities for different component frequencies. This is shown at long distances by their separation into two parts, namely a high-frequency component of the order of 5 000 cycles per sec. and a later-arriving component of the order of 500 cycles per sec.

The work carried out under the auspices of the Union during the International Polar Year, 1932–1933, in which the British expedition to Tromso played an important part, was reviewed. Agreement between the results in Tromso, Canada, and America, during the eclipse of the sun on the 31st August, 1932, appears to indicate that the normal ionizing agency for Region "E" was the ultra-violet light from the sun, and it appears conclusive that during periods of intense magnetic activity no energy is returned from the ionosphere.

Amongst the recommendations of the Congress are included the investigation of the mechanism of the generation of electrical oscillations of ultra-high frequency and a study of the propagation of ultra-short waves.

### *Interference of Electrical Plant with the Reception of Radio Broadcasting.*

This subject has been very prominently to the fore both in this country and elsewhere.* A Committee of the Institution representative of all the interests concerned is now dealing with the question. It is also the subject of international collaboration through the International Electrotechnical Commission, who are primarily concerned with the correlation of methods of measurement of interference and the consideration of international standards of permissible strength of the interference field.

The author is indebted to the British Broadcasting Corporation, the General Post Office, Marconi's Wireless Telegraph Co., Ltd., and Standard Telephones and Cables, Ltd., for much of the information in this review on the developments in broadcasting and the progress made in commercial services and other applications of the radio art.

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* A. Morris: "The Interference of Electrical Plant with the Reception of Radio Broadcasting," *Journal I.E.E.*, 1934, vol. 74, p. 245.

# ALTERNATING-CURRENT PERMEABILITY AND THE BRIDGE METHOD OF MAGNETIC TESTING.*

By C. E. Webb, B.Sc., Associate Member, and L. H. Ford, B.Sc.

[From the National Physical Laboratory.]

(*Paper first received 27th March, and in final form 19th April,* 1934.)

## SUMMARY.

A method for the direct measurement of the quantities involved in the a.c. permeability of a specimen, namely $B_{max.}$ and $H_{max.}$, is described. It is applied in an investigation of the dependence of the a.c. permeability of commercial sheet materials on frequency and wave-shape at power and telephonic frequencies. In agreement with other observers, the effect of frequency is found to be neglible up to 500 cycles per sec. apart from a reduction, attributable to eddy currents, at magnetizing forces for which the permeability is high.

Tests on a range of specimens with magnetizations giving wave-shape conditions varying between sinusoidal voltage and sinusoidal current, failed to show the increased permeability with approximation to a sinusoidal current wave which was observed by Lombardi and McLachlan. Within the accuracy of the measurements, the permeability appeared independent of wave-shape between these two practical limiting conditions.

In the second part of the paper a comparison between the results of loss measurements on magnetic materials by bridge and wattmeter methods is described. The discrepancies observed are shown to be entirely attributable to the errors in the bridge results due to the presence of harmonics, and the conditions under which the bridge method may be used satisfactorily for iron-testing, at both power and telephonic frequencies, are deduced.

## **Part 1.** ALTERNATING-CURRENT PERMEABILITY.

### INTRODUCTION.

The effective permeability of a material subjected to alternating magnetization is more difficult to define satisfactorily than the d.c. or static permeability. Under alternating magnetization not only does the relation between $B$ and $H$ vary continuously throughout the cycle, but in all ordinary commercial materials the purely magnetic properties are masked to a greater or less degree by the effects of eddy currents, which are dependent on the resistivity, thickness of lamination, etc., of the material. By analogy with the d.c. permeability the ratio between the maximum values of $B$ and $H$ during a cycle of magnetization should be adopted as the definition of the a.c. permeability. Whereas, however, with d.c. magnetization $B_{max.}$ and $H_{max.}$ are corresponding values on the hysteresis loop, with a.c. magnetization owing to the influence of eddy currents the tip of the loop is rounded and the maximum values of $B$ and $H$ do not normally occur simultaneously. This effect cannot be dealt with satisfactorily by resolving the magnetizing current into power and wattless components and regarding the latter alone as operative in magnetizing the specimen, for, owing to the non-linearity of the $B/H$ curve and the influence of hysteresis, the wave-shapes of $B$ and $H$ are usually different and the results of a resolution based on the fundamental components only are likely to be very misleading.

Theoretically the a.c. permeability should be taken as the ratio between the maximum flux density and the true maximum magnetizing force acting on the material, i.e. the resultant of the applied magnetizing force and the magnetizing force due to eddy currents. This latter quantity, however, cannot be directly measured or calculated with precision and, furthermore, is not uniform in magnitude or phase throughout the material. A definition based on it would not, therefore, be of practical utility, and since what is required in practice is to be able to calculate the magnetizing force which must be applied to produce a given maximum flux density it is preferable to define the a.c permeability as the ratio between the maximum flux density and the maximum applied magnetizing force, i.e. $\mu_{A.C.} = B_{max.}/H_{max.}$.

The theoretical objection that the permeability so defined does not depend solely on the strictly magnetic properties of the material is of little practical significance, while the definition has the advantage of allowing the effect of the frequency of the alternating magnetization to be clearly seen, since the quantities involved are directly comparable with those used in determining the d.c. permeability. On the other hand it is an inconvenience that the definition involves the maximum values of $B$ and $H$, since a.c. measurements usually yield r.m.s. values and the determination from these of the maximum values requires a knowledge of the wave-shapes of the quantities concerned. The method of finding the a.c. permeability by measuring the r.m.s. values of current and induced voltage, and thence deducing the maximum values of $H$ and $B$ by the aid of oscillograms of the current and voltage waves, has sometimes been adopted (e.g. by Morris and Langford† and N. W. McLachlan‡) but is long and tedious. A much quicker method, first suggested to the authors by the late Dr. D. W. Dye, was briefly described in an appendix to a previous paper.§ This method, a further account of which is, for convenience, given below, allows the quantities $B_{max.}$ and $H_{max.}$ to be read directly, and its simplicity and rapidity make it very suitable for investigating the variability of the a.c. permeability at power or telephonic frequencies with the conditions of magnetization, e.g. frequency and wave-shape.

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* The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (except those from abroad) should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

† See Reference (1).

‡ *Ibid.*, (2).

§ *Ibid.*, (3).

Comparisons between the d.c. and a.c. permeabilities of materials have been made by numerous investigators. A comprehensive and critical survey of the earlier work on the subject was given by Bown,[*] and since the date of his paper (1917) further results bearing on the problem have been obtained by, among others, Kaufmann,[†] Kaufmann and Pokar,[‡] Krüger and Plendl,[§] Niwa, Matura and Sugiura,[||] Brasey,[¶] Neumann,[**] Lapp,[††] Bozorth,[‡‡] Kühlewein,[§§] and M. Wien.[||||]

Summarizing the results recorded, it appears that when eddy currents are negligible the a.c. permeability with a sinusoidal flux wave is identical with that found ballistically, at least up to frequencies of many thousands of cycles per sec., while if the effect of eddy currents is appreciable the a.c. permeability is reduced owing to the rounding of the tips of the hysteresis loop. A decrease of permeability with increased frequency has been observed, however, at low magnetizing forces which is attributed to "magnetic after-effect."[¶¶]

The effect on the a.c. permeability of a departure from a sinusoidal induced e.m.f. wave, involving the introduction of harmonics into the flux wave, has been examined by several investigators, whose results were not entirely in agreement. Thus Niwa, Matura and Sugiura,[||] and Lloyd,[***] found no appreciable change in the a.c. permeability provided the wave did not become re-entrant. On the other hand Lombardi[*] and McLachlan[†] found that with a sinusoidal magnetizing current the a.c. permeability was higher than the d.c. value at the same magnetizing force and that the maximum flux density occurred earlier in the cycle than the maximum applied magnetizing force. In view of the divergence between the results obtained by different investigators on the effect of wave-shape on the a.c. permeability, special attention was given to this problem in the measurements to be described.

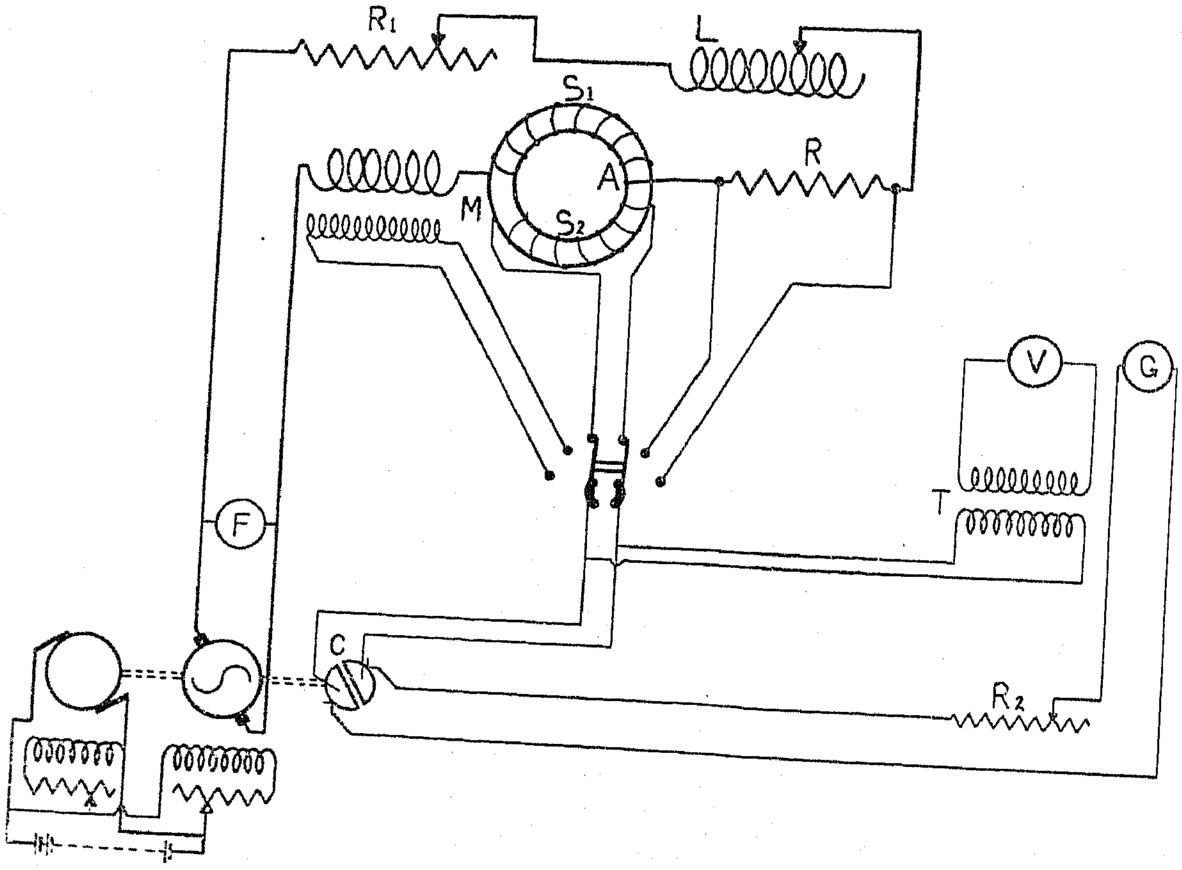

FIG. 1.—Circuit for a.c. permeability measurement.

## METHOD OF TESTING.

The circuit used to measure $H_{max.}$ and $B_{max.}$ directly under alternating magnetization is shown in Fig. 1. The magnetizing current is supplied from a motor-driven alternator having a wide range of speed-adjustment. Two such machines were available, for tests at power and telephonic frequencies respectively. In series with the primary coil ($S_1$) on the specimen is connected the low-resistance primary winding of an air-cored mutual inductance (M) of variable magnitude. Values of $B_{max.}$ and $H_{max.}$ are calculated from measurements of the mean voltages induced in the secondary windings on the specimen and the mutual inductance respectively.

The apparatus used to measure the mean voltages operates on the principle employed by Sahulka,[‡] Townsend,[§] Lloyd,[||] and others, and comprises a bifilar moving-coil reflecting galvanometer (G) in series with a high resistance ($R_2$) and a synchronous commutator (C) carried on the alternator shaft. The positions of the brushes on the commutator are adjusted to give the maximum deflection on the galvanometer, and the mean voltage is deduced from this deflection using the d.c. calibration of the instrument.

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[*] See Reference (4).
[†] *Ibid.*, (5).
[‡] *Ibid.*, (6).
[§] *Ibid.*, (7).
[||] *Ibid.*, (8).
[¶] *Ibid.*, (9).
[**] *Ibid.*, (10).
[††] *Ibid.*, (11).
[‡‡] *Ibid.*, (12).
[§§] *Ibid.*, (13).
[||||] *Ibid.*, (14).
[¶¶] *Ibid.*, (13).
[***] *Ibid.*, (15).

[*] See Reference (16).
[†] *Ibid.*, (2).
[‡] *Ibid.*, (17).
[§] *Ibid.*, (18).
[||] *Ibid.*, (19).

In making a measurement of permeability the frequency is first set using a reed frequency meter (F, Fig. 1) at power frequencies or by beats against a tuning fork at telephonic frequencies. The alternator excitation is then adjusted to give the mean voltage corresponding to the desired $B_{max.}$ across the secondary winding $S_2$ on the specimen, in accordance with the relation

$$V_{mean} = 4fN_2AB_{max.} \times 10^{-8}$$

where $f$ = frequency, in cycles per sec.; $N_2$ = number of secondary turns on specimen; and $A$ = cross-sectional area of specimen, in cm$^2$.

The form factor of the induced e.m.f. wave may be obtained if required by reading the r.m.s. voltage on the electrostatic voltmeter (V) connected in parallel with the $V_{mean}$ apparatus either directly or through the transformer T.

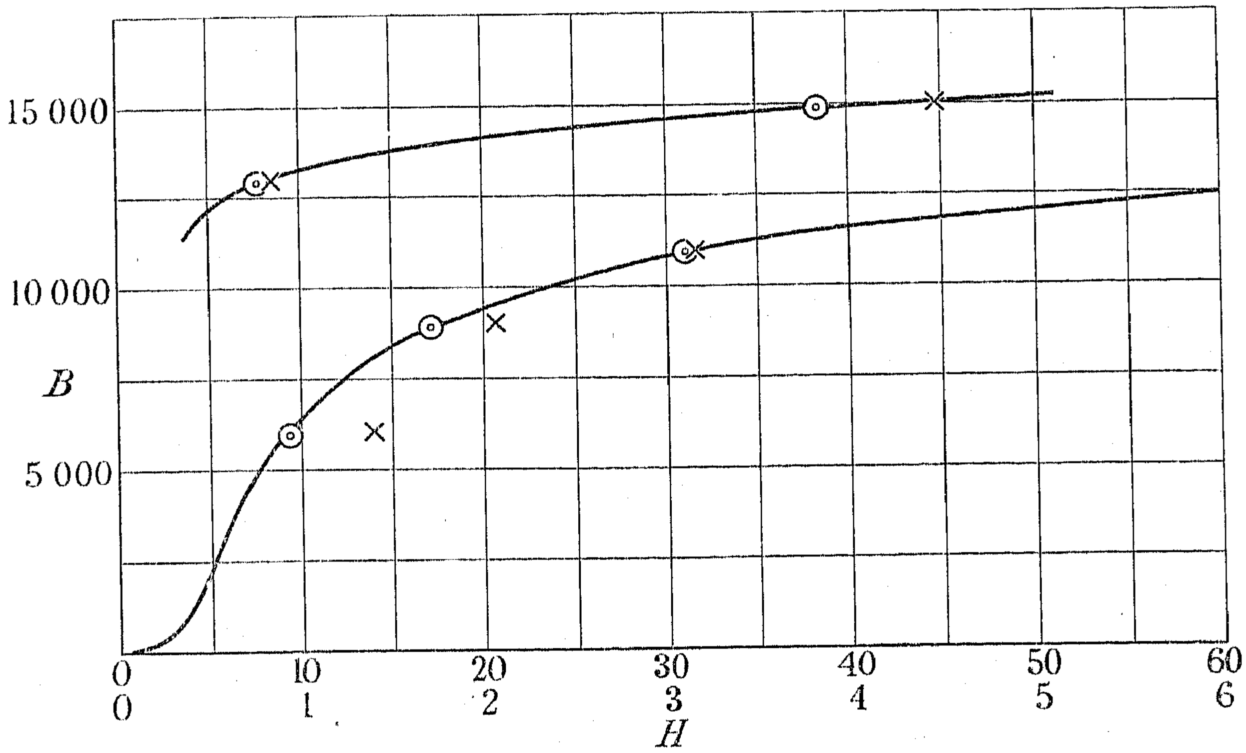

FIG. 2.—Comparison of d.c. and a.c. permeabilities on 0·3-mm stalloy sheet.

——— D.C. results.
⊙ ⊙ ⊙ A.C. results, 50 cycles per sec.
× × × A.C. results, 500 cycles per sec.

The commutator is next connected to the secondary of the mutual inductance M, the brushes are readjusted, and $H_{max.}$ is calculated from the observed mean voltage $V'_{mean}$, using the relation

$$V'_{mean} = 4fMI_{max.} = \frac{4fM \,.\, 10lH_{max.}}{4N_1}$$

where $M$ = mutual inductance, in henrys; $l$ = mean length of specimen, in cm; and $N_1$ = number of primary turns on specimen.

It is to be noted that the displacement of the brushes between the two settings is a measure of the phase displacement between $B_{max.}$ and $H_{max.}$, and indicates the degree of rounding of the tip of the hysteresis loop.

If the form factor of the current wave is required, both the $V_{mean}$ apparatus and the electrostatic voltmeter are connected across a non-inductive resistance (R) in the primary circuit and simultaneous readings are taken.

An adjustable resistance ($R_1$) and inductance (L) are inserted in the primary circuit to vary the wave-shape, and, if necessary in order to obtain a sinusoidal current wave, a condenser may be connected in series with the inductance to give resonance with the supply frequency.

## RESULTS OBTAINED.

### (a) *Comparison of D.C. and A.C. Permeabilities.*

The $B/H$ curves for a number of samples of various grades and thicknesses of material were determined both ballistically and with alternating magnetization giving an approximately sinusoidal induced e.m.f. Frequencies of 50 and 500 cycles per sec. were employed.

Typical results are shown in Figs. 2 and 3, which refer respectively to 0·3-mm high-resistance (stalloy) rings and 0·4-mm low-resistance (lohys) rings. On the stalloy rings practical agreement between ballistic and a.c. permeabilities is obtained at 50 cycles per sec. throughout the range of $H$ examined, but at 500 cycles per sec. such agreement is obtained only above $H = 5$ (approx.). In a similar test at 500 cycles per sec. on rings of similar material approximately 0·1 mm thick the discrepancy at low magnetizing forces was much smaller, and practical agreement was obtained above about $H = 2$. On the lohys rings even at 50 cycles per sec. agreement between ballistic and a.c. results is obtained only above $H = 5$.

The relative brush settings in the measurements of $B_{max.}$ and $H_{max.}$ showed that when the a.c. permeability was equal to the d.c. value, $B_{max.}$ and $H_{max.}$ were practically in phase; when, at the lower magnetizations, the a.c. permeability fell below the d.c. value, $B_{max.}$ lagged behind $H_{max.}$ by an amount roughly proportional to the difference between the permeabilities.

Some measurements were also made on strips built up with corner-pieces in a Lloyd square, this form of sample being treated as a ring in the way described in Appendix 3 of the previous paper.* The results were similar to those obtained on rings.

### (*b*) *Effect of Wave-shape.*

Tests were made at a number of flux densities and with various wave-shape conditions on the 0·4-mm lohys rings and the 0·1-mm stalloy rings. The wave-shape conditions ranged from a sinusoidal, or practically sinusoidal, induced e.m.f. wave to a practically sinusoidal current wave, the e.m.f. wave being progressively distorted during the transition. At each wave-shape, measurements were made of the voltage and current form-factors and of the mean voltage across the secondary of the mutual inductance M.

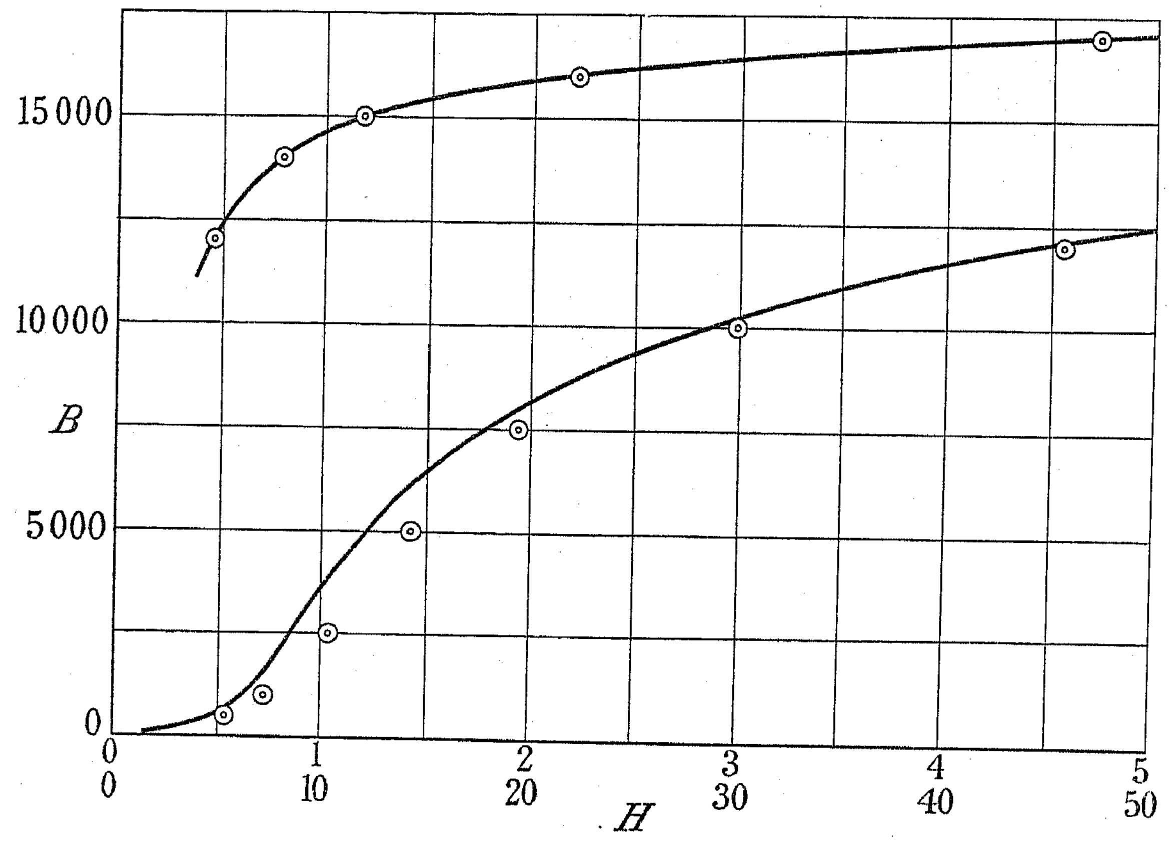

FIG. 3.—Comparison of d.c. and a.c. permeabilities on 0·4-mm lohys sheet.

——— D.C. results.
⊙ ⊙ ⊙ A.C. results, 50 cycles per sec.

The results obtained on the lohys ring are given in Table 1; it will be seen that over the wide range of form factors employed the value of $H_{max.}$ for a given $B_{max.}$ is unaltered by change of wave-shape, within the limits of accuracy of the measurements, except at $B_{max.} = 5\,000$. At this flux density, as shown in Fig. 3, the value of $H_{max.}$ required with sinusoidal voltage was appreciably higher than the corresponding d.c. magnetizing force, and with increased voltage form-factor the value of $H_{max.}$ was still higher, i.e. the permeability decreased still farther below the d.c. value. The lag of $B_{max.}$ behind $H_{max.}$, as shown by the brush settings, also increased as the voltage wave became more distorted.

The results obtained on the 0·1-mm stalloy rings are not reproduced, but at each value of $B_{max.}$ the values of $H_{max.}$ obtained were identical, within the accuracy of the measurements, for all conditions of wave-shape from sinusoidal voltage to sinusoidal current. The sinusoidal-current conditions involved very distorted voltage waves at the higher flux densities, the voltage form-factor being as high as 4 in some tests.

In no case was any indication observed of an increase in the permeability above the value for a sinusoidal voltage wave (which has been shown to be equal to, or less than, the d.c. permeability) as the current wave was made to approximate to a sinusoidal form; nor was any tendency detected for the flux density to reach its maximum before the applied magnetizing force.

## DISCUSSION OF RESULTS.

The agreement between the a.c. and d.c. permeabilities at high flux densities and the fact that the differences observed at low magnetizing forces increase with the conductivity of the material, the thickness of lamination, and the form factor of the induced e.m.f., suggest strongly that these differences are due mainly, if not entirely, to eddy currents. The results of the comparison of a.c. and d.c. permeabilities are thus consistent with those of other investigators in indicating the practical identity of the values obtained by the two methods of measurement, at least up to telephonic frequencies, apart from the effects of eddy currents.

The results obtained with sinusoidal and approximately sinusoidal magnetizing currents are in conflict with those of Lombardi and McLachlan and confirm those of Lloyd and of Niwa, Matura, and Sugiura. The authors are unable to explain the disagreement between their observations and those of Lombardi and McLachlan, both of whose investigations appear to have been carried out with great care and thoroughness. It should be pointed out, however, that Lombardi's and McLachlan's results, although at first sight consistent, were actually to some extent contradictory. Thus Lombardi's measurements were made on fine wire at approximately 100 cycles per sec. and he attributed the increased permeability with a sinusoidal current wave to the influence of high-frequency eddy currents resulting from the very rapid change of flux density—estimated to be $60 \times 10^6$ lines per cm$^2$ per sec. in one test—and to the absence of appreciable eddy currents of the fundamental frequency, which, he stated, normally masked the effect. McLachlan, on the other hand, used lohys sheet of ordinary commercial thicknesses, closely resembling the material on which the results recorded in Table 1 were obtained. For such material it is well known that at power frequencies the eddy currents of fundamental frequency are by no means negligible, as is confirmed by the results shown in Fig. 3, and in accordance with Lombardi's experience, therefore, no excess of a.c. over d.c. permeability was to be expected. Moreover, the variation with the flux density of the excess observed was quite different in the two sets of results; Lombardi found a steady increase with increasing flux density from zero at the lowest densities to 14 per cent at a magnetizing force corresponding to $B = 16\,000$, while McLachlan obtained a practically constant percentage excess (approximately 10 per cent) over the whole range of magnetizing force tested. In view of the great variation in the shape of the hysteresis loop as the magnetizing force is increased, this latter result seems *a priori* a most improbable one.

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* See Reference (3).

TABLE 1.

*Effect of Wave-shape on A.C. Permeability of Lohys Rings.*

Mean circumferential length = 42·4 cm. Cross-section ($A$) = 0·769 cm$^2$. Thickness of material = $0{\cdot}4_3$ mm. Primary turns ($N_1$) = 600; hence $H/I$ = 17·8. Frequency = 50 cycles per sec.

| $B_{max.}$ | Form factor of induced e.m.f. ($fv$) | Mutual inductance ($M$) | $V_{mean}$ on secondary of mutual inductance | $H_{max.}$ | Form factor of current ($f_I$) |
|---|---|---|---|---|---|
| 5 000 | 1·120 | 0·05 | 0·829 | 1·475 | 1·075 |
| | 1·198 | | 0·869 | 1·546 | 1·105 |
| 10 000 | 1·135 | 0·05 | 1·680 | 2·99 | 1·076 |
| | 1·260 | | 1·682 | 2·995 | 1·110 |
| | 1·327 | | 1·676 | 2·98 | 1·112 |
| | 1·370 | | 1·675 | 2·98 | Resonating circuit |
| 15 000 | 1·196 | 0·01 | 1·30 | 11·6 | 1·222 |
| | 1·616 | | 1·303 | 11·6 | 1·136 |
| | 1·802 | | 1·29 | 11·5 | 1·120 |
| | 1·98 | | 1·312 | 11·7 | Resonating circuit |
| 17 500 | 1·320 | 0·001 | 0·721 | 64·3 | 1·392 |
| | 2·38 | | 0·723 | 64·5 | 1·142 |

Since an increase of at least 10 per cent in the flux density corresponding to a given applied magnetizing force was observed by both investigators at flux densities in the neighbourhood of $B = 15\,000$, an increase in the effective magnetizing force of at least 50 per cent must be postulated, and as the maximum flux density was found to occur appreciably before the applied magnetizing force reached its maximum the additional magnetizing force to be provided by the eddy currents must be somewhat higher than this. The magnetizing force required is, moreover, in the opposite direction from that to be expected on first principles since it must occur at the end of a rapid increase in the flux density. Non-uniform flux distribution might help to produce the observed effect, but it is difficult to believe that a magnetizing force of such magnitude could result from this cause. The whole effect is indeed very difficult to account for, and, although both the authors have suggested high-frequency eddy currents as a general explanation, no detailed theory of the way in which the apparent increase in permeability is produced has been worked out.

The authors' tests were made by a direct method of measurement on a number of specimens of commercial sheet material, including one closely resembling McLachlan's materials and one for which the eddy-current conditions should approximate to those in Lombardi's samples. Certain measurements were also repeated using a method almost identical with that of McLachlan and deducing the values of $B_{max.}$ and $H_{max.}$ from r.m.s. measurements by the aid of oscillograms. The results, within the accuracy of measurement (which was rather less than that obtained by the commutator method), agreed with those previously obtained. As these tests entirely failed to show increased permeability with a sinusoidal current wave, it seems likely that the effect previously recorded is not to be regarded as a genuine property of the materials, but was rather due to some characteristic of the particular circuits employed. At least, if genuine, it is not a general property of magnetic materials.

The matter is of some practical importance in the measurement of a.c. permeability since it is not always possible to obtain sinusoidal voltage conditions, while in bridge methods of magnetic testing (which are discussed further in Part 2) the sinusoidal current condition is normally employed. Any considerable variation of permeability with wave-shape would cause differences between the results of such measurements and of d.c. tests, and would lessen the value of a.c. methods. Apart, however, from the reduction in the apparent permeability with increased distortion of the flux wave, which was observed where the effects of eddy currents of fundamental frequency were appreciable, the authors' tests show that the a.c. method of measurement described gives results which are not affected by changes of wave-shape between the practical limiting conditions of sinusoidal voltage and sinusoidal current.

The method is a very quick and convenient one, provided the necessary equipment (synchronous commutator, etc.) is available, and there seems no reason why it should not be employed in commercial testing of sheet material, particularly at flux densities above $B = 10\,000$. The possibility of applying it, where a very high degree of accuracy is not required, to strips built up with corner-pieces in a loss-testing square also adds to its practical convenience, since it allows permeability and loss measurements to be made on the same specimens and with the same testing equipment.

## **Part 2.** THE BRIDGE METHOD OF MAGNETIC TESTING.

### INTRODUCTION.

The principal methods in use for the testing of magnetic materials under alternating magnetization are of two types: (*a*) Deflectional methods involving the measurement of the losses by means of a wattmeter and the determination of the flux density from a measurement of induced voltage. (*b*) Bridge and potentiometer methods.

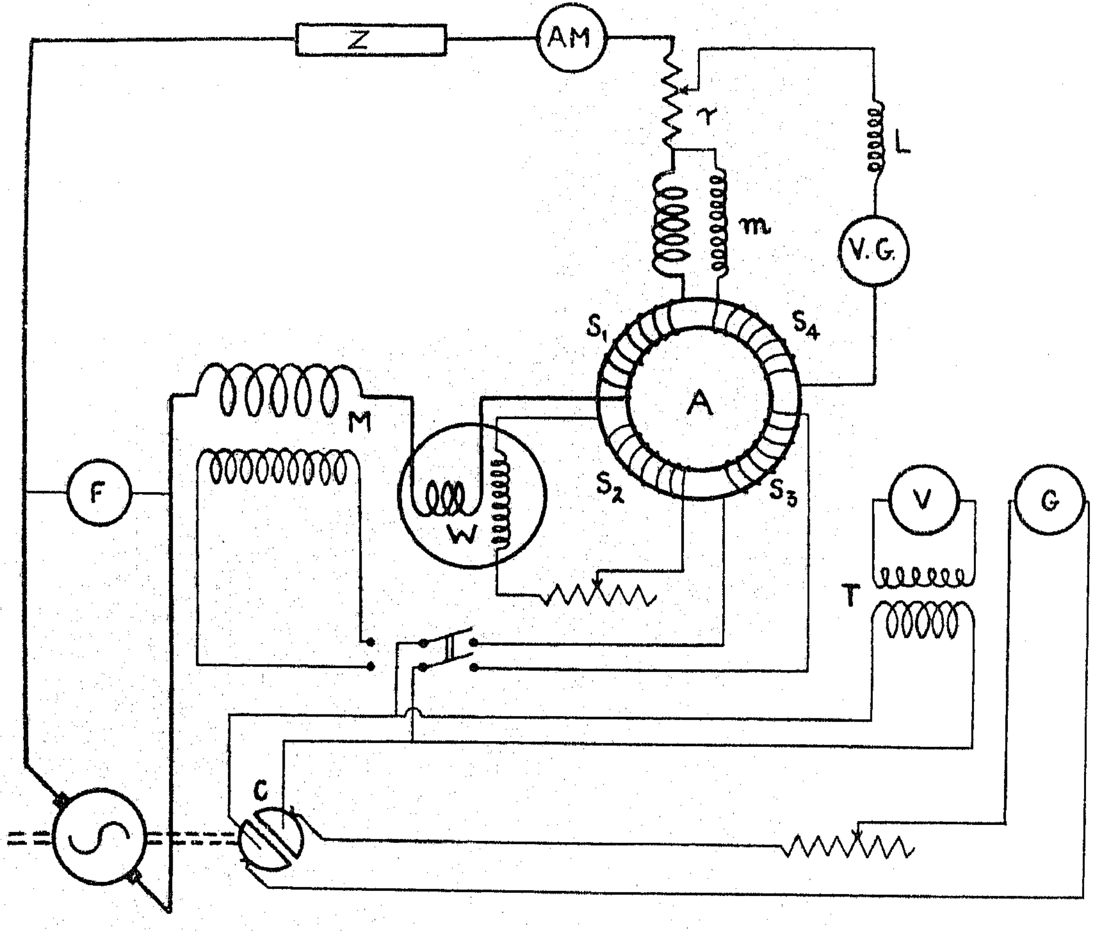

FIG. 4.—Circuit for comparison of bridge and wattmeter measurements.

Each of these has definite limits to its practical utility. Thus wattmeter methods suffer from lack of sensitivity at low flux densities, while bridge methods only deal with the fundamental components of the voltage and current waves and are therefore liable to error when appreciable harmonics are present.

The tests to be described were carried out to compare the results obtained by the bridge and wattmeter methods over a wide range of flux density and frequency, and, in particular, to determine the limits of accurate measurement by the bridge method.

### METHODS OF MEASUREMENT.

The principle of the wattmeter method of measuring iron losses is too well known to need explanation, and the details of the method and apparatus used have been described in a previous paper.* It may be mentioned, however, that the wattmeter employed was of the reflecting dynamometer pattern, of high sensitivity, and constructed largely of marble in order to minimize eddy currents and consequent errors at high frequencies. It was known to be reliable up to 800 cycles per sec.

One of the most convenient bridge methods of iron-loss measurement is that due to A. Campbell,† and this was adopted throughout the investigation. The general conclusions reached are applicable, however, to any form of bridge or potentiometer method of magnetic testing. So that a direct comparison between the results of the two methods could be made, the instruments required for the wattmeter measurements and the bridge circuits were connected simultaneously to the test-specimen. A diagram of the combined circuits is given in Fig. 4, the vibration galvanometer V.G. shown being replaced by a telephone for measurements at audio frequencies.

As the balance condition of the bridge relates only to the fundamental components of the voltages in the bridge secondary circuit, for accurate loss measurements either a sinusoidal induced voltage in the windings on the specimen or a sinusoidal magnetizing current is necessary. As it is not in general possible to ensure a sinusoidal voltage across the primary on the specimen, it is usual to aim at the sinusoidal current condition by inserting in the primary circuit either a high non-inductive resistance if the supply voltage is accurately sinusoidal or an air-cored inductance or series resonance circuit if it departs appreciably from a sinusoidal waveform. This series impedance is represented by Z in Fig. 4.

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* See Reference (3).

† *Ibid.*, (20).

Particulars of the sheet-material ring samples used are given in Table 2. After it had been set to the desired frequency and $B_{max.}$ in the specimen, the bridge was balanced by adjustments of $m$ and $r$, and readings were taken of the primary current, wattmeter deflection, r.m.s. voltage on the secondary ($S_3$), and mean voltage on the secondary of the air-cored inductance (M).

TABLE 2.

*Particulars of Specimens Tested (rings).*

| No. | Material | Density | Total mass | Mean diameter | Cross-section | Windings | |
|---|---|---|---|---|---|---|---|
| | | | | | | Primary turns | Secondary turns |
| | | | g | cm | cm² | | |
| 1 | Lohys .. .. .. | 7·80 | 4 270 | 23·0 | 7·58 | 80, 10 (twice) | 100, 50, 20 (twice), 10 |
| 2 | 50 per cent nickel-iron | 8·22 | 794 | 13·5 | 2·275 | 50, 10 (twice) | 100, 40, 10 |
| 3 | Stalloy .. .. | 7·55 | 57·8 | 7·78 | 0·313 | 100, 30, 10 | 25, 10 (twice), 5 |

The total loss was calculated from the bridge readings using the relation

$$\text{Loss} = rI_1^2 \times \frac{\text{Number of turns on } S_1}{\text{Number of turns on } S_4}$$

and the value of $H_{max.}$ was derived from the mean voltage on the air-cored inductance by the method of Part 1. The flux density indicated by the bridge readings was also determined by means of Campbell's approximate formula*

$$\omega^2 N_4^2 \Phi^2_{R.M.S.} = (r^2 + \omega^2 m^2) I_1^2 \times 10^{16}$$

$$\text{whence} \quad B_{max.} = \frac{\sqrt{2} I_1 \sqrt{(r^2 + \omega^2 m^2)} \times 10^8}{\omega N_4 A}$$

where $I_1$, $m$, and $r$ are in practical units, $N_4$ is the number of turns on $S_4$, and $A$ is the cross-sectional area of the specimen in cm².

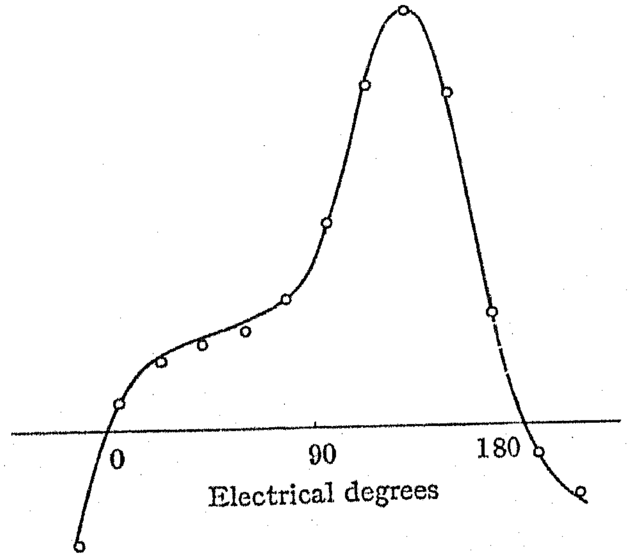

FIG. 5.—Wave-shape obtained by means of synchronous commutator, compared with that obtained by oscillogram.

——— Oscillogram.
O O O O Points found by synchronous commutator.

In order to investigate the effects of harmonic components, the wave-shapes of $B$ and $H$ were derived in certain tests by rotating the pair of movable brushes on the synchronous commutator into various angular settings and noting the galvanometer reading for each setting. By plotting the readings on an angle base the wave-shapes of $B$ and $H$ could be obtained in the correct relative phase. The short-circuiting of the segments as the brushes cross the gaps is liable to cause error at points near the zero-line of the wave, since the voltage at the moment of commutation has then its largest values. A comparison of the wave obtained by the commutator method with that given by an oscillograph for a fairly peaky current wave showed, however, that the distortion arising from this cause was very small (see Fig. 5). The form-factor values calculated from the oscillograph and commutator curves were respectively 1·222 and 1·223, the difference being well within the probable experimental error.

## EXPERIMENTAL RESULTS.

A series of measurements was first made on specimens Nos. 1 and 2 at 50 cycles per sec. at various flux densities with as large a series resistance in the magnetizing circuit as would allow the desired flux density to be attained with the alternator kept fully excited. For comparison a few tests were also made without series impedance ($Z = 0$, Fig. 4). Typical results are shown in Table 3, which also gives for certain tests the errors to be expected in the bridge results, owing to the presence of harmonics, calculated from the observed wave-shapes of $B$ and $H$. The method of computing these errors is illustrated by an example in the Appendix.

It will be seen from the results in Table 3 that, to the accuracy of the comparison (about 1 per cent), the power losses found by the two methods agree well except at a high flux density. The observed discrepancies, on both power loss and $B_{max.}$, are shown to be satisfactorily accounted for by the influence of harmonics on the results of the bridge method.

To approximate more closely to a sinusoidal current wave-shape, especially at high flux densities, the magnetizing circuit was adjusted to series resonance at the supply frequency. Tests were made under these conditions at 50 and 500 cycles per sec. on specimens Nos. 1 and 3, and the results are given in Table 4.

The discrepancies in the tests at 500 cycles per sec. between the power-loss results above $B = 6\,000$ and between the $B_{max.}$ values even at the lowest flux densities

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* See Reference (20).

### TABLE 3.

*Comparison of Results by Bridge and Wattmeter Methods at* 50 *cycles per sec., with and without Series Resistance.*

| $B_{max.}$ | | Power loss (watts) | | Percentage discrepancies (bridge−wattmeter) | | | |
|---|---|---|---|---|---|---|---|
| | | | | $B_{max.}$ | | Power loss | |
| Commutator | Bridge | Wattmeter | Bridge | Measured | Calculated | Measured | Calculated |
| (1) *With Series Resistance. Specimen No.* 1 | | | | | | | |
| 200 | 196·5 | 0·0116 | 0·0116 | − 1·7 | − 1·0 | 0·0 | — |
| 1 000 | 1 002 | 0·284 | 0·281 | + 0·2 | + 0·5 | − 1·1 | — |
| 2 000 | 2 013 | 1·012 | 1·007 | + 0·7 | — | − 0·5 | — |
| 3 600 | 3 725 | 2·90 | 2·88 | + 3·4 | + 3·0 | − 0·7 | 0·0 |
| 12 500 | 13 760 | 28·5 | 29·5 | + 10·1 | + 11·4 | + 3·5 | + 3·3 |
| *Specimen No.* 2 | | | | | | | |
| 1 000 | 982 | 0·00992 | 0·00982 | − 1·8 | − 1·7 | − 1·0 | — |
| 2 000 | 2 003 | 0·0443 | 0·0438 | + 0·2 | 0·0 | − 1·1 | — |
| 4 000 | 4 040 | 0·165 | 0·163 | + 1·0 | + 0·5 | − 1·2 | — |
| 6 000 | 6 280 | 0·347 | 0·347 | + 4·7 | + 4·2 | 0·0 | — |
| (2) *Without Series Resistance. Specimen No.* 1 | | | | | | | |
| 200 | 192 | 0·0112 | 0·01115 | − 4·0 | − 3·0 | − 0·5 | — |
| 1 000 | 958 | 0·280 | 0·278 | − 4·2 | — | − 0·7 | — |
| 12 500 | 13 380 | 26·2 | 27·8 | + 7·0 | — | + 6·1 | — |

### TABLE 4.

*Comparison of Results by Bridge and Wattmeter Methods with Series Resonating Circuit at* 50 *and* 500 *cycles per sec.*

| $B_{max.}$ | | Power loss (watts) | | Percentage discrepancies (bridge−wattmeter) | |
|---|---|---|---|---|---|
| Commutator | Bridge | Wattmeter | Bridge | $B_{max.}$ | Power loss |
| (1) *Frequency* = 50 *cycles per sec. Specimen No.* 1 | | | | | |
| 50 | 50·2 | 0·000586 | 0·000590 | + 0·4 | +0·7 |
| 500 | 507 | 0·0742 | 0·0741 | + 1·4 | −0·1 |
| 2 000 | 2 042 | 1·023 | 1·018 | + 2·1 | −0·5 |
| 5 000 | 5 225 | 5·09 | 5·07 | + 4·5 | −0·4 |
| 8 000 | 8 540 | 11·97 | 11·95 | + 6·8 | −0·2 |
| 10 000 | 10 910 | 18·35 | 18·35 | + 9·1 | 0 |
| 12 500 | 14 060 | 29·6 | 29·6 | +12·5 | 0 |
| (2) *Frequency* = 500 *cycles per sec. Specimen No.* 1 | | | | | |
| 50 | 51·2 | 0·0230 | 0·0231 | + 2·4 | +0·4 |
| 200 | 203 | 0·378 | 0·375 | + 1·5 | −0·8 |
| 500 | 512 | 2·26 | 2·29 | + 2·4 | +1·3 |
| 2 000 | 2 012 | 26·9 | 26·8 | + 0·6 | −0·4 |
| *Specimen No.* 3 | | | | | |
| 2 000 | 2 090 | 0·113 | 0·112 | + 4·5 | −0·9 |
| 4 000 | 4 170 | 0·382 | 0·381 | + 4·3 | −0·3 |
| 6 000 | 6 350 | 0·804 | 0·792 | + 5·8 | −1·5 |
| 8 000 | 8 810 | 1·45 | 1·42 | +10·1 | −2·1 |
| 10 000 | 11 300 | 2·45 | 2·34 | +13·0 | −4·5 |

were shown by analyses of the wave-shapes in a few representative cases to be due to a small residual harmonic, the 500-cycle supply voltage having a pronounced 3rd harmonic which it was not possible to suppress entirely with the apparatus available.

Comparative measurements were also made by bridge and wattmeter methods with asymmetrical hysteresis cycles obtained by superposing d.c. and a.c. magnetizations, the relative magnitudes of which were varied over a wide range. The discrepancies between the results obtained were closely similar to those with symmetrical alternating magnetization.

## Discussion and Conclusions.

In ordinary commercial magnetic materials the permeability changes little with flux density up to, say, $B = 200$, and with a sinusoidal $H$-wave the $B$-wave is also practically sinusoidal. The bridge method is therefore satisfactory at these low flux densities provided a sinusoidal magnetizing current is employed. At higher flux densities distortion of the flux-wave results from the non-proportionality between $B$ and $H$. From the results in Tables 3 and 4 it is clear that in consequence of this distortion the values of $B_{max.}$ deduced from bridge readings may be appreciably in error at flux densities as low as $B = 500$. To relate the power losses to the flux density, therefore, it is necessary to combine the bridge measurement with a determination of $B_{max.}$ by means of the synchronous commutator or some other method independent of wave-shape.

The bridge method is shown to be reliable for loss measurements up to high values of $B_{max.}$ provided the current is kept sinusoidal. This condition may be fulfilled without special precautions up to a flux density of about $B = 8\,000$ with a supply voltage of good wave-shape, but at higher flux densities or with a supply voltage departing seriously from a sinusoidal wave-shape (if the harmonics exceed, say, 10 per cent of the fundamental) a tuned magnetizing circuit is essential for accurate loss measurements. With the limitations indicated the method is applicable at considerably higher flux densities than those at which it is generally used, and may be of value when a suitable wattmeter is not available, e.g. in tests on very small specimens where high sensitivity is required and at telephonic frequencies where only a specially constructed wattmeter, such as that used in these tests, could be relied on.

A practical drawback to the use of the bridge with a sinusoidal magnetizing current is that the loss-results obtained are somewhat indefinite since the voltage form-factor, on the square of which the eddy-current loss depends, varies greatly for a very small departure of the current wave from a sinusoidal form. Moreover, loss-results for a very distorted flux-wave are of little practical utility to the designer. At power frequencies a correction may be made for this distortion, and the losses reduced to a standard form-factor, by testing at two different frequencies and separating the losses in the usual way; if the voltage form-factor is appreciably different at the two frequencies the separation may still be made by a method of successive approximations. At telephonic frequencies, however, owing to non-uniform flux distribution the losses do not follow the simple law of variation with frequency sufficiently closely for a satisfactory separation to be effected in this way. The method can therefore only be applied conveniently at low flux densities where the voltage wave departs little from sinusoidal form, say below $B = 4\,000$.

Summarizing the conclusions reached, it appears that:—

(1) The wattmeter and bridge methods give consistent loss measurements provided errors in the bridge results due to harmonics are avoided. In general this necessitates a sinusoidal magnetizing current.

(2) Under these conditions the bridge method, in combination with the synchronous commutator method of measuring $B_{max.}$, may be conveniently used for loss measurements up to high flux densities at power frequency.

(3) At telephonic frequencies under the same conditions the bridge method, although capable of giving accurate results, is not convenient in practice except at fairly low flux densities at which the distortion of the flux wave is small.

(4) Permeability measurements based on bridge readings are not reliable except at very low flux densities, say below $B = 500$, owing to the influence of harmonics.

## APPENDIX.

### CALCULATION OF ERRORS IN BRIDGE RESULTS DUE TO HARMONICS.

In the calculation given below, the errors due to harmonics are determined for $B = 12\,500$ in specimen No. 1 with series resistance (see Table 3).

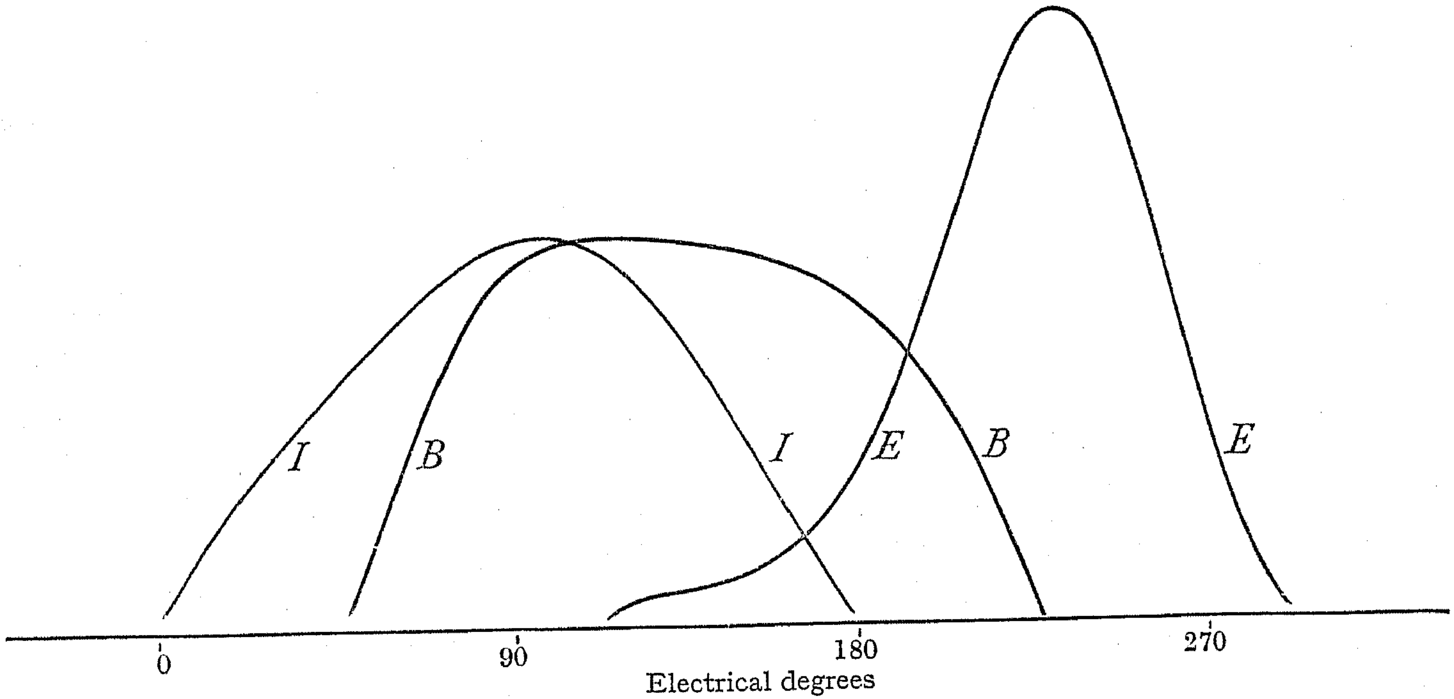

FIG. 6.—Current, flux, and calculated e.m.f. wave-shapes.

The current and flux waves, each reduced to an amplitude of 100 units, are shown in Fig. 6.

Applying a simple method of harmonic analysis and measuring phase angles from the point at which the current curve crosses the zero-line in the positive direction, the following expressions are obtained for the two waves:—

$$B = 111 \cdot 4 \sin(\omega t - 46^\circ) + 13 \cdot 9 \sin(3\omega t + 201^\circ) + 1 \cdot 4 \sin(5\omega t + 64^\circ)$$

$$H = 97 \cdot 2 \sin(\omega t - 4^\circ) + 5 \cdot 1 \sin(3\omega t + 101^\circ)$$

Differentiating $B$ with respect to time and ignoring constants common to all terms, since only relative amplitudes and phases are required, we obtain

$$E = 111 \cdot 4 \cos(\omega t - 46^\circ) + 42 \cos(3\omega t + 201^\circ) + 7 \cos(5\omega t + 64^\circ)$$

$$= 111 \cdot 4 \sin(\omega t + 44^\circ) + 42 \sin(3\omega t + 291^\circ) + 7 \sin(5\omega t + 154^\circ)$$

This curve is also shown in Fig. 6.

In the power-loss measurement errors may occur in two ways owing to the presence of harmonics:—

(1) By the inclusion of harmonics in the r.m.s. current measured by AM (Fig. 4), while only the fundamental is involved in the balance condition.

$$\text{Percentage error} = 100 \times (5\cdot 1)^2/(97\cdot 2)^2 = +\,0\cdot 3$$

(2) By power of harmonic frequencies not affecting the balance.

$$\text{Power of fundamental frequency} \propto (111\cdot 4 \times 97\cdot 2/2) \cos 48^\circ \propto 3\,610$$

$$\text{Power of 3rd-harmonic frequency} \propto (42 \times 5\cdot 1/2) \cos 190^\circ \propto -\,106\cdot 5$$

$\therefore$ Percentage error due to omission of harmonic power

$$= [106\cdot 5/(3\,610 - 106\cdot 5)] \times 100 = +\,3\cdot 0$$

$\therefore$ Total error due to presence of harmonics $= +\,3\cdot 3$ per cent.

The observed discrepancy between the bridge and wattmeter results was $+\,3\cdot 5$ per cent.

In the determination of $B_{max.}$ from the bridge readings a small error again results from the inclusion of harmonics in the r.m.s. primary current measured, but the principal source of error is the neglect of the harmonics in the induced e.m.f. The value found therefore corresponds to the amplitude of the fundamental of the flux wave, 111·4, instead of the true maximum, 100. The percentage error is thus $+\,11\cdot 4$, which is in fair agreement with the observed discrepancy between bridge and commutator results of $+\,10\cdot 1$ per cent.

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# THE THERMAL RESISTANCE AND CURRENT-CARRYING CAPACITY OF THREE-CORE SCREENED AND S.L.-TYPE CABLES.[*]

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(*Paper first received* 14*th February, and in final form* 4*th July,* 1934.)

## SUMMARY.

A simple experimental method of determining the thermal effect of the screens in 3-core screened-type cables is described and a comparison made between the results obtained and those derived from other sources. A basic diagram embodying the experimental results is given which covers a wide range of conductor sizes and insulation thicknesses and enables the influence of different types of screens to be readily determined. From this diagram a practical chart has been prepared showing the thermal resistance of 0·04- to 0·5-sq. in. 3-core cables with the two types of screens commonly employed, namely (1) 3-mil copper tape; (2) 1·5-mil aluminium foil.

In general, it is found that for practical sizes of cables copper-tape screens reduce the thermal resistance by about 30 to 40 per cent, and aluminium-foil screens by about 15 to 30 per cent.

A method of calculating the thermal resistance of S.L.-type cables is given from which it appears that, contrary to popular ideas on the subject, this type of cable is not always the best from a thermal point of view.

## (1) INTRODUCTION.

The screened-core type of cable originally suggested by Höchstädter is now in common use for 3-core cables operating at voltages of 11 kV and above, and it is well known that the metallic screens, although not primarily introduced for that purpose, exert a beneficial influence on the thermal rating by facilitating the passage of heat from the central portions of the cable. The screen material is generally aluminium foil or copper tape, and notwithstanding the thinness of the metallic layer (1–3 mils) its important effect on the heat-dissipating properties of the cable can be realized when it is remembered that the thermal conductivity of aluminium is of the order of 1 100 times, and that of copper 2 000 times, that of the impregnated paper forming the dielectric of the cable.

An idea of the nature and distribution of heat flow occurring under load conditions can be obtained from Fig. 1, which represents a 60° sector of a 3-core screened cable, one of the radii (XM) coinciding with a core diameter. From principles of symmetry it is only necessary to consider the thermal phenomena taking place in this sector, the thermal resistance[†] of the complete cable being one-sixth of the value for the sector.

The heat generated flows more or less radially from the conductor and on arriving at the screen has, in general, two paths by which it may reach the sheath: (i) circumferentially along the screen, (ii) through the filler.

Suppose the screen AM to be divided into twelve elements, AB, BC, CD, etc., subtending angles of 15° at the centre of the core. The points A, B, C, D, etc., are then joined to the conductor surface, cutting off equal sectors of core insulation. D, E, F, etc., are also joined to the sheath by producing the lines XD, XE, XF, etc., to meet the sheath at *d*, *e*, *f*, etc., thus cutting off ten slices from the filler. The series of resistances formed by the core sectors, screen elements, and filler slices, can then be represented diagrammatically as in Fig. 2(*a*), the total resistance of the network corresponding to the thermal resistance of the cable sector.

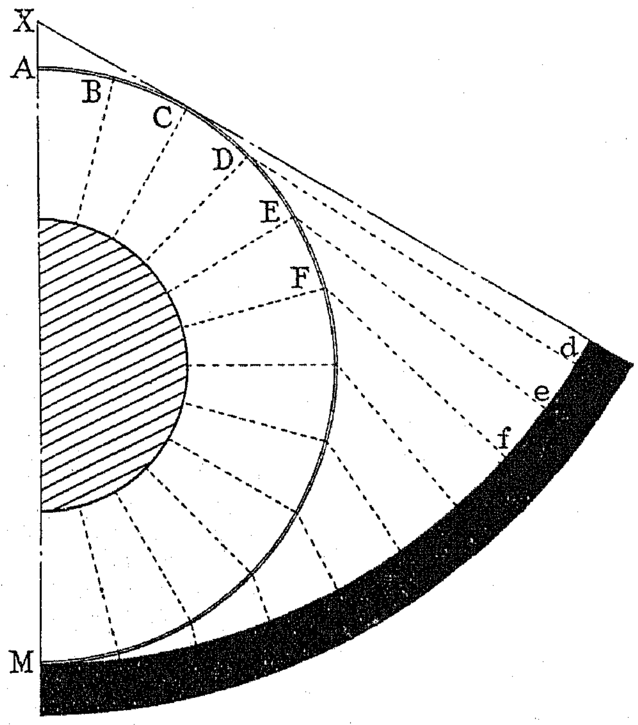

FIG. 1.—60° sector of screened cable.

Owing to discrepancies between the actual flow lines and the artificial lines assumed in Fig. 1, it is not claimed that this correspondence is exact. On the other hand the divergence in the lines of heat flow will not be serious except in the filler space, where a small error is relatively unimportant. Hence it is considered that the results obtained on the assumed basis will be a close approximation to the exact values, which could only be ascertained by more elaborate methods than the one to be described. In any case the results based on any arbitrary system of flow lines will be on the safe side, as the actual heat flow follows the path of least resistance.

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[*] The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (except those from abroad) should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

[†] Unless indicated otherwise by the context, the term "thermal resistance" of a cable is used to denote the internal thermal resistance between conductors and the nearest overall metallic layer, i.e. between conductors and sheath in the case of screened cables, and between conductors and armouring in the case of S.L.-type cables.

At present there is no general agreement on the quantitative thermal effect of the screens. It is understood to be the practice of British cable manufacturers to take the thermal resistance of screened-type cable as 85 per cent of the thermal resistance of an unscreened cable having the same dimensions, no differentiation being made between different screen materials and thicknesses.

In America Simons's formula* for thermal resistance is commonly used:—

$$S = \frac{1}{6}\sqrt{\left(\frac{R\rho}{t_s}K\log_e\frac{R}{r}\right)}\coth\left\{\pi\sqrt{\left[\frac{R\rho}{t_sK\log_e(R/r)}\right]}\right\} \quad (1)$$

thermal ohms per cm

where $R$ = radius of screen; $r$ = radius of conductor; $t_s$ = thickness of screen; $\rho$ = thermal resistivity of screen material; and $K$ = thermal resistivity of dielectric ($R$, $r$, and $t_s$, are all measured in the same units; $\rho$ and $K$ are expressed in thermal ohms per cm cube.)

The above formula is based on an infinite number of screen elements, and all the heat is assumed to reach the sheath circumferentially through the screens, the alternative path through the fillers being neglected.

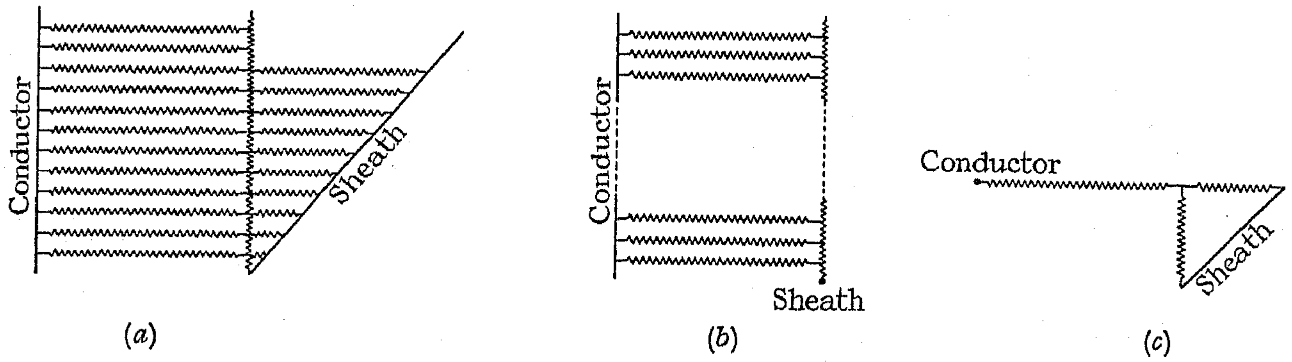

FIG. 2.—Equivalent networks for determination of heat flow in screened cable.

The diagrammatic arrangement of the various thermal resistances is thus as shown in Fig. 2(*b*).

Another method of determining the thermal resistance of screened-type cables, suggested by Beavis,† ingeniously attempts to remove the limitations of the above formula by combining with it an expression for the apparent thermal resistance of the fillers derived from the following formula‡ (due to Simons) for the thermal resistance of belted-type cable with zero belt thickness:—

$$S_u = \frac{0\cdot 85K}{6\pi}\log_e\left(\frac{8\cdot 3t_c}{d}+1\right) \quad . \quad . \quad . \quad (2)$$

thermal ohms per cm

where $t_c$ = core-insulation thickness and $d$ = conductor diameter, both being measured in the same units.

In brief, the method is as follows. The thermal resistance of the cable is first calculated by formula (1) and from this is subtracted the thermal resistance of the three cores in parallel, given by

$$S_c = \frac{K}{6\pi}\log_e\frac{R}{r} \text{ thermal ohms per cm}$$

The difference is the apparent circumferential thermal resistance $S_s$ of the screens, since in the derivation of formula (1) it was assumed that the entire heat flow took place through the screens. Secondly, the cable is regarded as unscreened, its thermal resistance being calculated by formula (2), which applies to the case where all the heat flow takes place via the fillers; and, on again subtracting the value of $S_c$, the apparent thermal resistance $S_w$ of the fillers is obtained. The apparent thermal resistances both of the screens and of the fillers having been obtained in this way, their combined resistance in parallel is added to the thermal resistance of the cores; in other words, the thermal resistance of the complete cable is given by

$$S = S_c + \frac{S_sS_w}{S_s + S_w} \text{ thermal ohms per cm} \quad . \quad (3)$$

Fig. 2(*c*) shows diagrammatically the arrangement; it should be noted that $S_w$ and $S_s$ are not the actual thermal-resistance values of the fillers and screens respectively, but fictitious values obtained as described above.

As regards other work on the subject, Konstantinowsky and Tschiassny* have published a comprehensive series of results based on experiments carried out with electrolytic models. This work will be referred to again at a later stage.

### (2) SCOPE AND METHOD OF TESTING.

The experimental work is based on the similarity between the heat flow in the system of thermal resistances shown in Fig. 2(*a*) and the flow of current in an analogous electrical network. When this network—representing to some particular scale the various thermal resistances involved—has been set up, all that remains is to measure its total resistance and convert the result to the thermal case by multiplying by the appropriate conversion factor.

From a general consideration of Fig. 1 it can be seen that: (i) From principles of similarity the thermal resistance of each of the filler slices is constant, irrespective of the size of the cable. (ii) The thermal resistance of the core sectors is dependent only upon the ratio $t_c/d$. (iii) For any particular screen material and constant screen thickness the circumferential thermal resistance of the screen elements depends only on the core diameter, i.e. it depends both on $t_c/d$ and on the actual value of $d$.

All the thermal-resistance values except those for the filler slices can be readily calculated, and the latter were determined by measurements taken on a large-scale drawing of the cable cross-section.

The apparatus used in the experiments took the form of a wooden framework about 11 ft. long by 1½ ft. wide, supported on trestles at a convenient height from the ground, and furnished with three fixed wooden cross-pieces AB, CD, and EF, as shown diagrammatically in Fig. 3. Between AB and CD were strung twelve No. 38 S.W.G. bare eureka wires to represent the sector thermal resistances, and between CD and EF twenty No. 18 S.W.G. bare eureka wires representing the screen-element thermal resistances. The requisite variability of these resistances was secured in the case of the core-sector resistances by a solid copper bar GH which was capable of sliding along the framework and could be secured to the eureka wires at any point between AB and CD. Similarly by means of copper short-circuiting strips on the movable cross-piece KL any desired screen-element resistance within the range of the apparatus could be set up. The filler resistances, which are constant, were represented by varying lengths of No. 38 or No. 18 S.W.G. insulated eureka wires strung between the terminals on cross-piece CD and a solid copper bar MN, as shown in the diagram.

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* See Reference (1).

† *Ibid.*, (2).

‡ *Ibid.*, (3).

* See References (4) and (5).

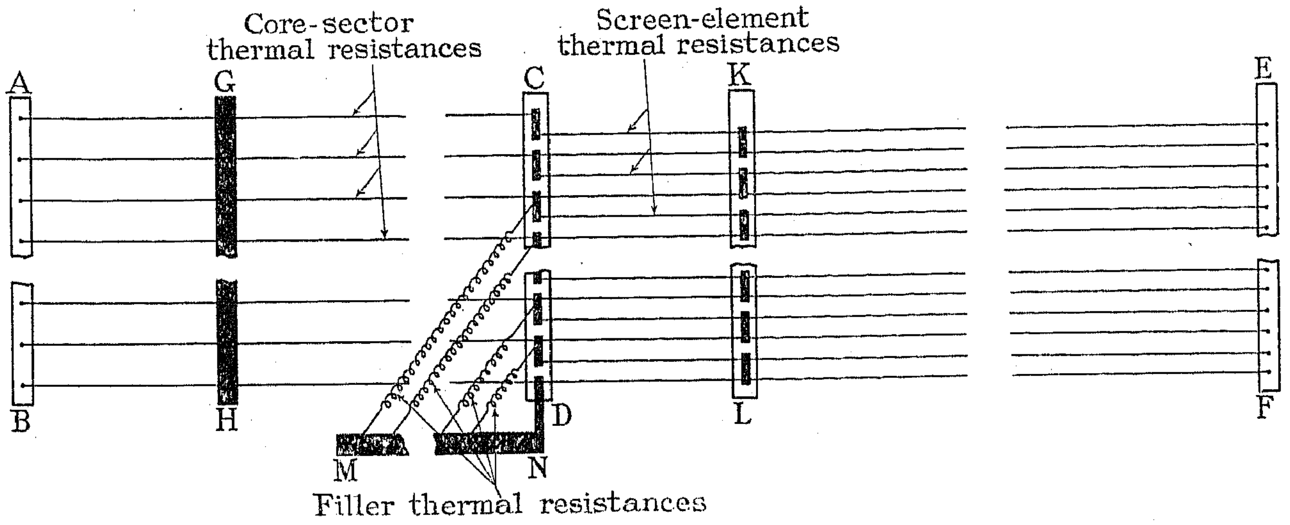

Core-sector thermal resistances
Screen-element thermal resistances
A
G
C
K
E
B
H
D
L
F
M
N
Filler thermal resistances

FIG. 3.—Diagrammatic representation of apparatus used in tests.

The method adopted in carrying out the tests was to set the copper bar GH as near the left-hand side of the apparatus as possible so as to embrace the maximum length of resistance wires between GH and CD, this position being taken to represent a $t_c/d$ ratio of 1·0. The slider KL was then moved so as to occupy in turn a series of positions previously marked out on the framework of the apparatus and approximately evenly spaced between the cross-pieces CD and EF. A measurement of the total resistance between the two copper bars GH and MN was made for each position of KL. The procedure was then repeated for $t_c/d$ ratios of 0·8, 0·6, 0·4, and 0·2. After they had been corrected for the resistance of the leads, etc., the readings of electrical resistance were multiplied by the factor 10·04 in order to convert the quantities actually measured into the corresponding values of thermal resistance for the complete cable. In deriving this factor the thermal resistivity of the dielectric was taken at the standard value of 550 thermal ohms per cm cube.

### (3) DISCUSSION OF RESULTS.

The results of the experiments are shown in the basic diagram (Fig. 4), which contains all the information in a concentrated form. By transformation of co-ordinates and replotting, a complete series of curves can be interpolated between the ones obtained experimentally. The diagram is thus rendered suitable for determining the thermal resistances of screened cables having widely varying dimensions and types of screens, the only calculation required being that of the screen-element thermal resistance, which is a simple matter. For any particular screen material and thickness, however, even this calculation can be rendered unnecessary, as will be shown later.

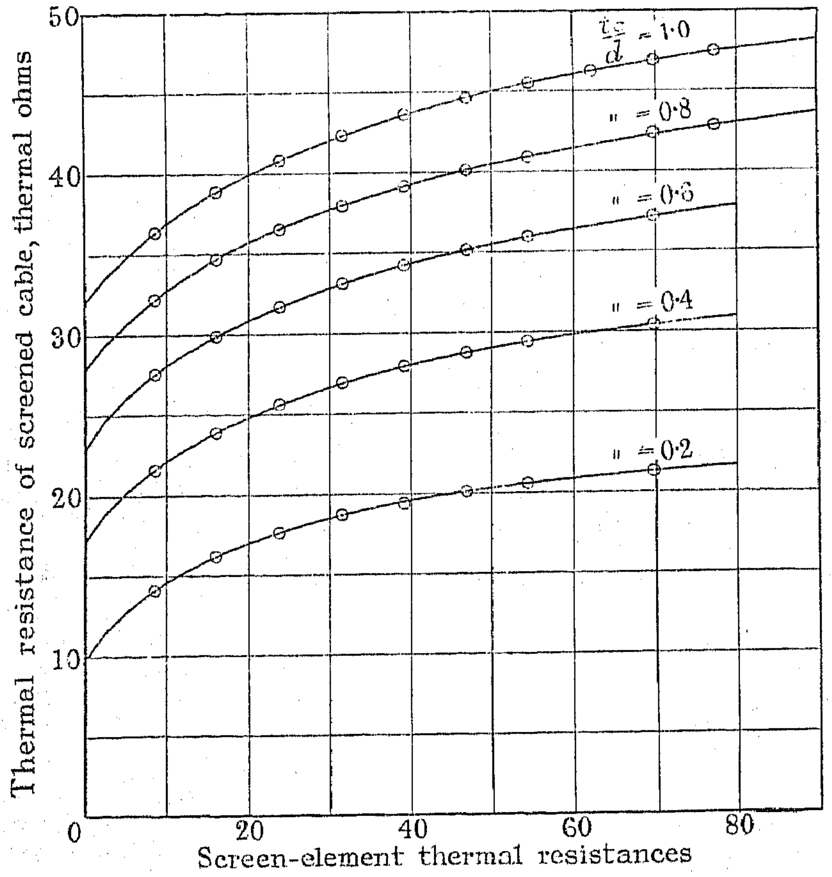
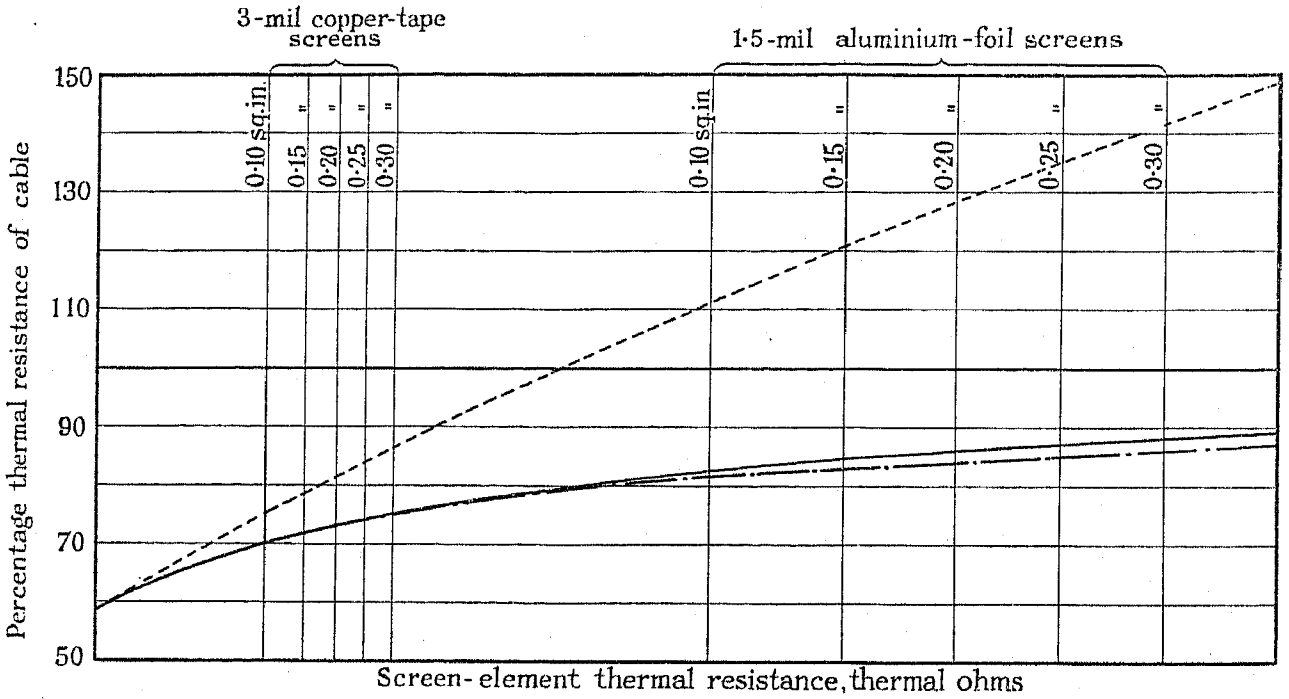


FIG. 4.—Thermal resistance of screened cables.

In Figs. 5A, 5B, 5C, 5D, and 5E, the curves have been replotted to a scale of percentages of the thermal resistance of an unscreened cable having the same dimensions. As the latter value depends only on $t_c/d$, the curve representing it forms the 100 per cent curve in each of the diagrams. The abscissæ in these diagrams are screen-element thermal resistances, but for clearness the only ones shown are those corresponding to 0·10-, 0·15-, 0·20-, 0·25-, and 0·30-sq. in. conductors with 3-mil copper-tape screens and 1·5-mil aluminium-foil screens respectively.

It will be seen that owing to the screens there are substantial reductions in the thermal resistance of the cable, particularly in the case of the copper-tape screens. The lower the circumferential thermal resistance of the screens, whether due to a material of greater conductivity or to a reduced $t_c/d$ ratio, the greater the percentage reduction in the thermal resistance of the cable. This might be expected, since the thermal resistance of the alternative path through the filler is constant and independent of both $t_c$ and $d$.

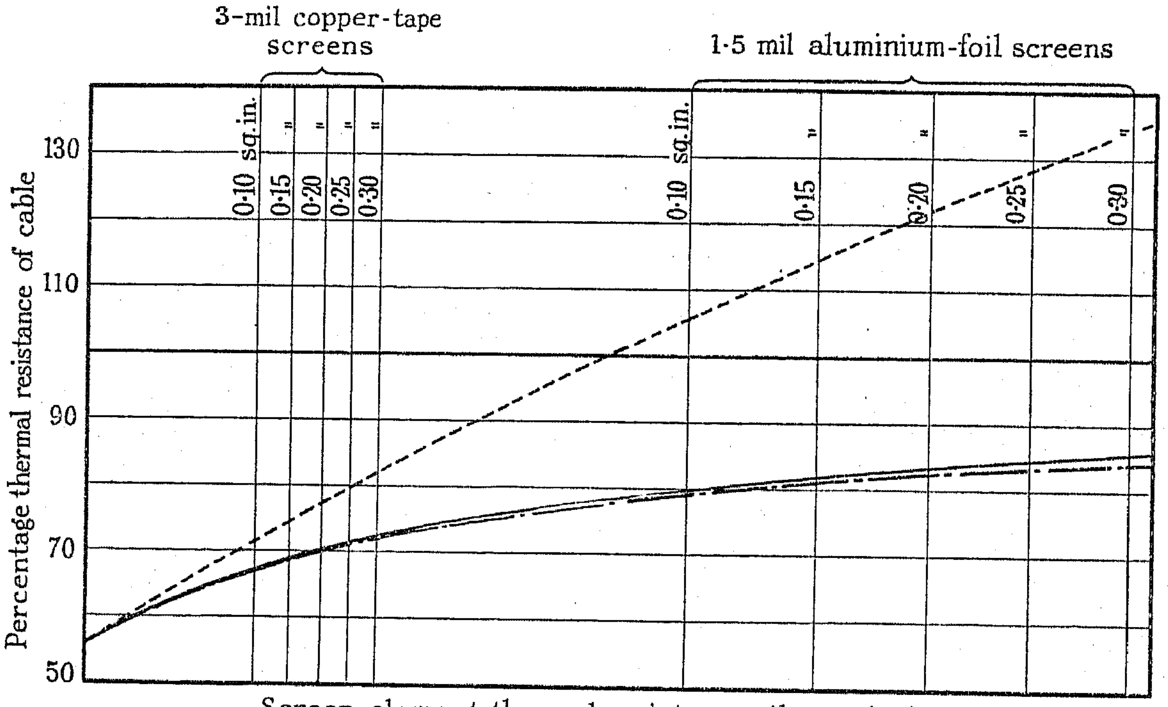
The values of thermal resistance have also been calculated from the screened-cable formula of Simons, and these values are shown in the diagrams by dotted lines. It will be noticed that these curves coincide with the experimental results for zero screen resistances, but otherwise they lie entirely above the experimental curves, the discrepancy being greater as the screen resistance increases. For some sizes of conductors with aluminium-foil screens the thermal resistances calculated by the formula come out even higher than the value $S_u$ for unscreened cable. This, of course, is due to the neglect of the filler path, so that as the circumferential screen resistance increases the total resistance of the cable rises.



Screen-element thermal resistance, thermal ohms

FIG. 5A.—Results for $t_c/d = 1·0$.

Simons formula — — — —
Beavis formula —— · ——
Experiment ————



Screen-element thermal resistance, thermal ohms

FIG. 5B.—Results for $t_c/d = 0·8$.

Simons formula — — — —
Beavis formula —— · ——
Experiment ————

and approaches infinity for infinite screen resistance, i.e. the case of the belted-type cable with zero belt-insulation. An investigation of the magnitude of the errors involved over the practical range of conductor sizes and voltages, viz. 0·04 to 0·5 sq. in. and 11 to 33 kV, shows that Simons's formula is from 3 per cent to 16 per cent high for 3-mil copper-tape screens and 16 per cent to 60 per cent high for 1·5-mil aluminium-foil screens. It seems evident that the employment of this formula for the case of aluminium-foil screens was not contemplated. It is almost universal practice in America to use copper-tape screens, and for this type the application of formula (1)—although somewhat inaccurate—gives results which are on the safe side.

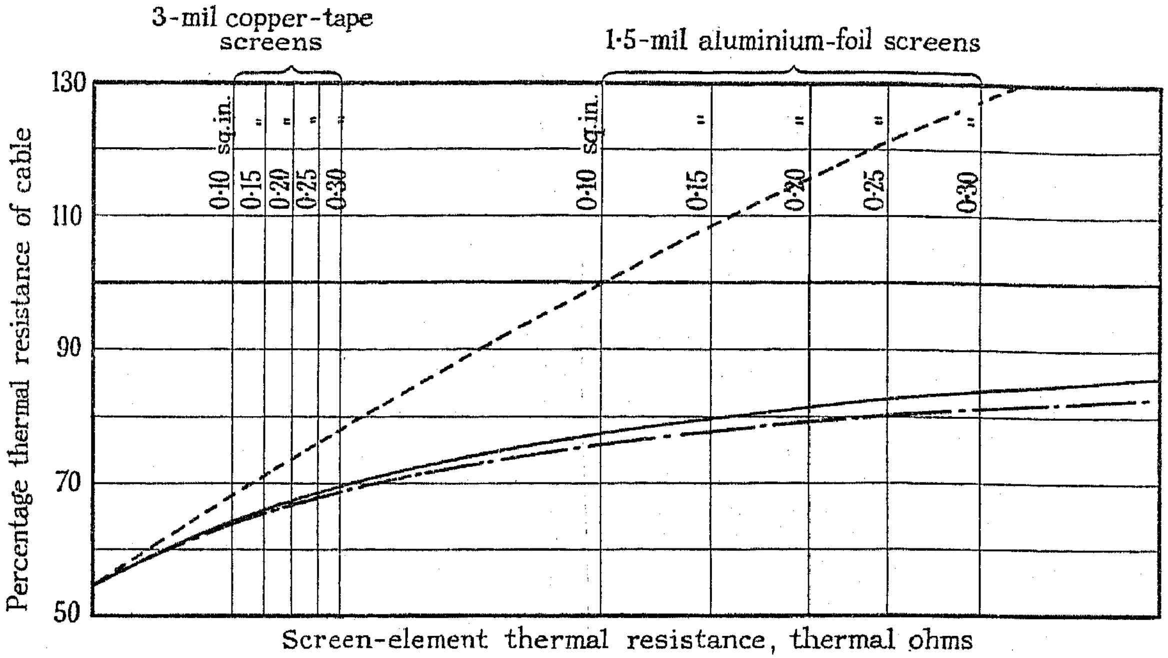


FIG. 5C.—Results for $t_c/d = 0\cdot6$.

Simons formula — — — —
Beavis formula ——·——
Experiment ————

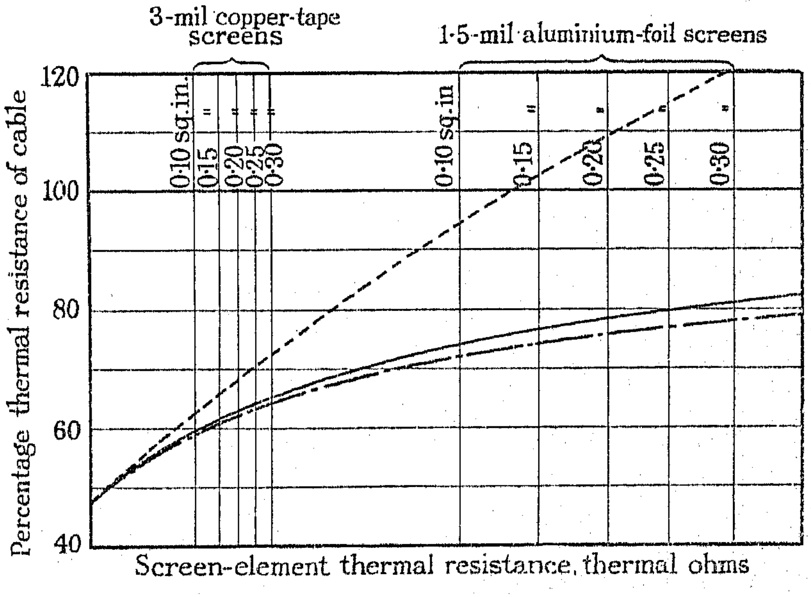


FIG. 5D.—Results for $t_c/d = 0\cdot4$.

Simons formula — — — —
Beavis formula ——·——
Experiment ————

Beavis's formula has also been used for calculating the thermal resistance, and the results are shown in the diagrams by chain-dotted lines. These lines are slightly below the curves experimentally obtained, but the discrepancy is not so great as in the case considered above. The experimental results and Beavis's curves are in exact agreement, however, to a certain extent, inasmuch as both curves have a lower limit of $S_c$ for screens of zero resistance and an upper limit of $S_u$ for infinite circumferential screen resistance.

The author did not become aware of the ingenious electrolytic method of Konstantinowsky and Tschiassny for obtaining the geometric factor of screened cables until some considerable time after the experimental work described in this paper had been completed. A comparison is therefore interesting and reveals that the maximum divergence between results obtained by the two different methods over the whole practical range of cable sizes is about 4 per cent. Over the bulk of

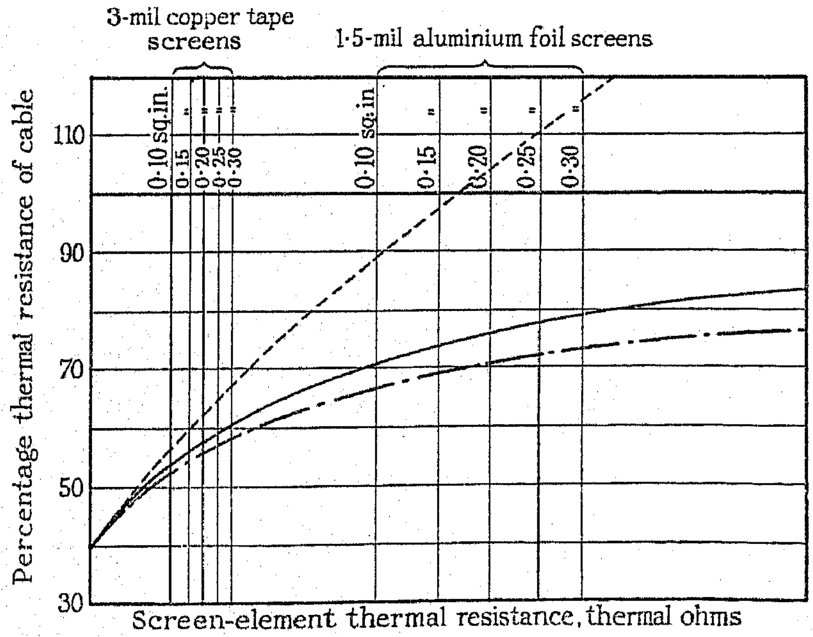


FIG. 5E.—Results for $t_c/d = 0\cdot2$.

Simons formula — — — —
Beavis formula ——·——
Experiment ————

this range the divergence is less than 3 per cent, which when translated into terms of current rating for cables laid under normal conditions means a variation of considerably less than 1 per cent in rating and is therefore insignificant. In general, the results obtained by Konstantinowsky and Tschiassny, if plotted in Figs. 5A, 5B, 5C, 5D, and 5E, would lie between the author's curve and that calculated by Beavis's formula, so that there is substantial agreement between the three sets of results.

### (4) INFLUENCE OF DIFFERENT SCREEN MATERIALS AND THICKNESSES.

In order to compare the influence of different types of screens, a typical 25 000-volt 3-core 0·20-sq. in. cable has been taken as an example and its thermal resistance obtained from Fig. 4 for copper-tape, aluminium-foil, and lead screens up to 10 mils thick.

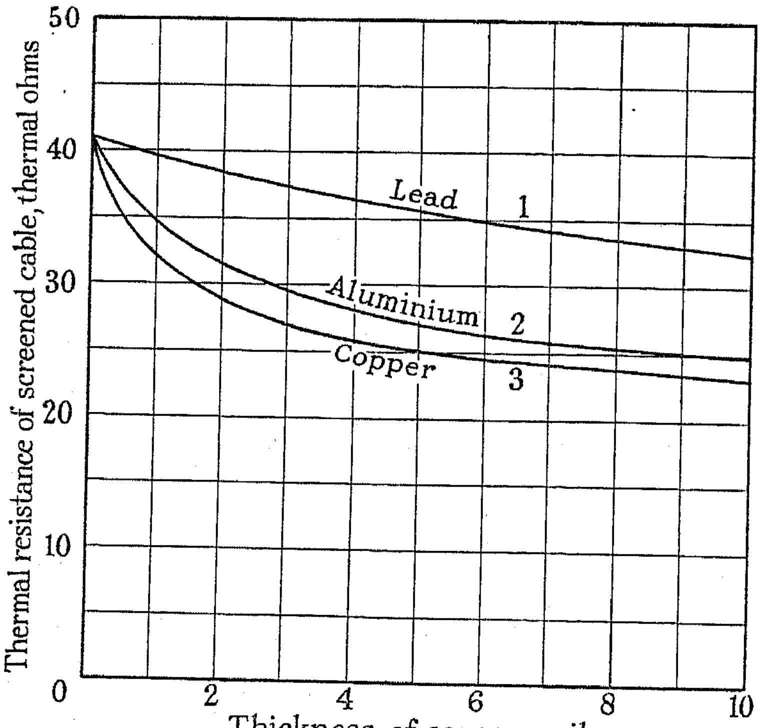


FIG. 6.—Effect of different types of screens on thermal resistance.

The results are shown by the curves of Fig. 6. All the curves converge to the value of 41·1 for the case of infinite screen resistance ($S_u = 41 \cdot 1$) and fall asymptotically to the limiting value of $S_c = 20 \cdot 8$ for zero screen resistance. The curve for lead is only shown for comparison, as owing to its higher thermal resistivity (2·9) as compared with the thermal resistivity of copper (0·27) a screen thickness of approximately 10 times that of copper is necessary to effect the same reduction in the thermal resistance of the cable.

In a similar way, the influence of the type and thickness of the metal screens can be investigated for any given case.

### (5) TEMPERATURE DISTRIBUTION IN SCREENS.

In order to obtain an idea of the temperature distribution in the screens for various cases, the apparatus was set up to represent a 25 000-volt 3-core 0·20-sq. in. cable with (*a*) 1·5-mil aluminium-foil screens, (*b*) 3-mil copper-tape screens, (*c*) 100-mil lead screens.

A definite small potential difference was applied between GH and MN (Fig. 3) and the corresponding potential difference measured between MN and the various terminals of the screen elements on the cross-piece CD.

Assuming that the temperature-difference between conductors and sheath in the actual cable is 10 deg. C., the three curves of Fig. 7 show the corresponding temperature-differences between the screens and the sheath. The cooling effect of the screens on the inner portion of the cable is very noticeable, the maximum temperature-rise in the screens above sheath being 6·5 deg. C. for the 1·5-mil aluminium-foil screens, 3·5 deg. C. for the 3-mil copper-tape screens, and only 1·7 deg. C. in the case of the 100-mil lead screens. With unscreened cable, on the other hand, the central portion of the cable between the cores would be substantially at full conductor temperature (10 deg. C. above that of the sheath).

### (6) PRACTICAL CHARTS.

From the basic diagram (Fig. 4) practical charts can be constructed for any particular type of screen to show the thermal resistance of screened cables for the usual range of conductor sizes. This has been done for 1·5-mil aluminium-foil screens and 3-mil copper-tape screens for conductor sizes between 0·04 and 0·5 sq. in., and the results are shown in Fig. 8. Other sizes of cables can be covered if necessary from the data given in Fig. 4. In preparing this chart (Fig. 8) the thermal resistivities of copper and aluminium have been taken as 0·27 and 0·48 thermal ohm per cm cube respectively, and the thermal resistivity of the dielectric at the standard value of 550 thermal ohms per cm cube.

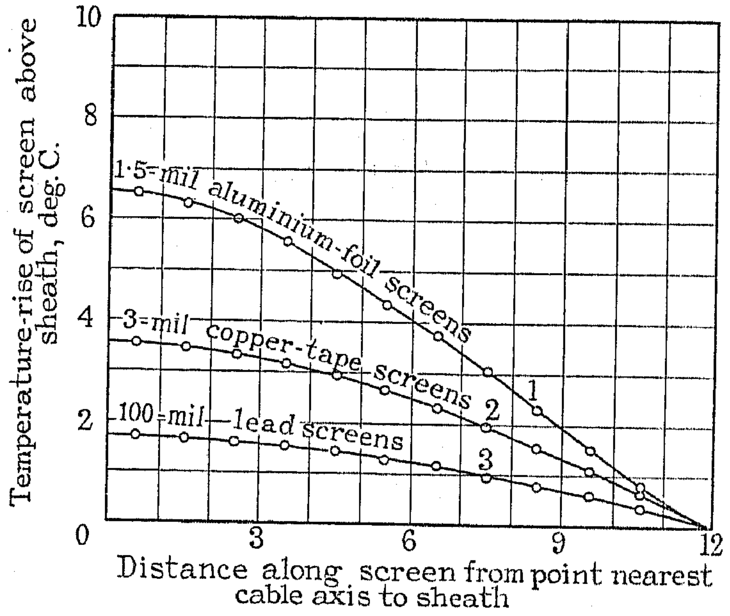


FIG. 7.—Temperature distribution in different types of screens.

### (7) CURRENT-CARRYING CAPACITY.

In determining the current-carrying capacity of cables, the thermal resistance external to the lead sheath must be taken into consideration. With the usual methods of installation this can be divided into three components: (i) The thermal resistance of the protective coverings, if any. (ii) The thermal resistance of the soil, if the cable is laid direct in the ground; or the corresponding resistance to the flow of heat from the cable surface to the air, if the cable is laid on racks. (iii) The apparent thermal resistance due to the presence of neighbouring loaded cables, if any. In practice the value of this external thermal resistance may vary between 1 and 4 times that of the internal thermal resistance of the cable.

Mathematically, the following relation exists:—

$$\frac{I_s}{I_u} = \sqrt{\left(\frac{k+1}{k+p}\right)} \quad . \quad . \quad . \quad . \quad (4)$$

where $I_s$ = permissible current in screened cable;
$I_u$ = permissible current in an unscreened cable of the same dimensions;
$k$ = ratio between external and internal thermal resistances of the unscreened cable;
and $p$ = ratio between thermal resistances of screened and unscreened cables.

Taking as an example two typical 25 000-volt 3-core 0·25-sq. in. armoured and served cables buried at a depth of 4 ft. with a horizontal spacing of 18 in. (soil resistivity = 180), the values of the above ratios are: $k = 2 \cdot 88$, $p = 0 \cdot 65$ for 3-mil copper-tape screens; and $p = 0 \cdot 80$ for 1·5-mil aluminium-foil screens. So that $I_s/I_u = \sqrt{(3 \cdot 88/3 \cdot 53)} = 1 \cdot 05$, for copper-tape screens; $I_s/I_u = \sqrt{(3 \cdot 88/3 \cdot 68)} = 1 \cdot 025$, for aluminium-foil screens. Thus the increases are 5 per cent and 2·5 per cent for copper-tape and aluminium-foil screens respectively. The above comparison assumes, of course, that the permissible temperature-rise is the same for each type of cable, and ignores the fact that it is standard practice to allow a higher operating temperature in the case of screened cables.

A general comparison on the same basis (i.e. taking into account only the thermal effect of the screens) between the ratings of screened and unscreened types for the sizes of cables and methods of installation usually employed shows that 3-mil copper-tape screened cables have an increased current-carrying capacity of 3–12 per cent, and 1·5-mil aluminium-foil screened cables an increased capacity of 2–8 per cent.

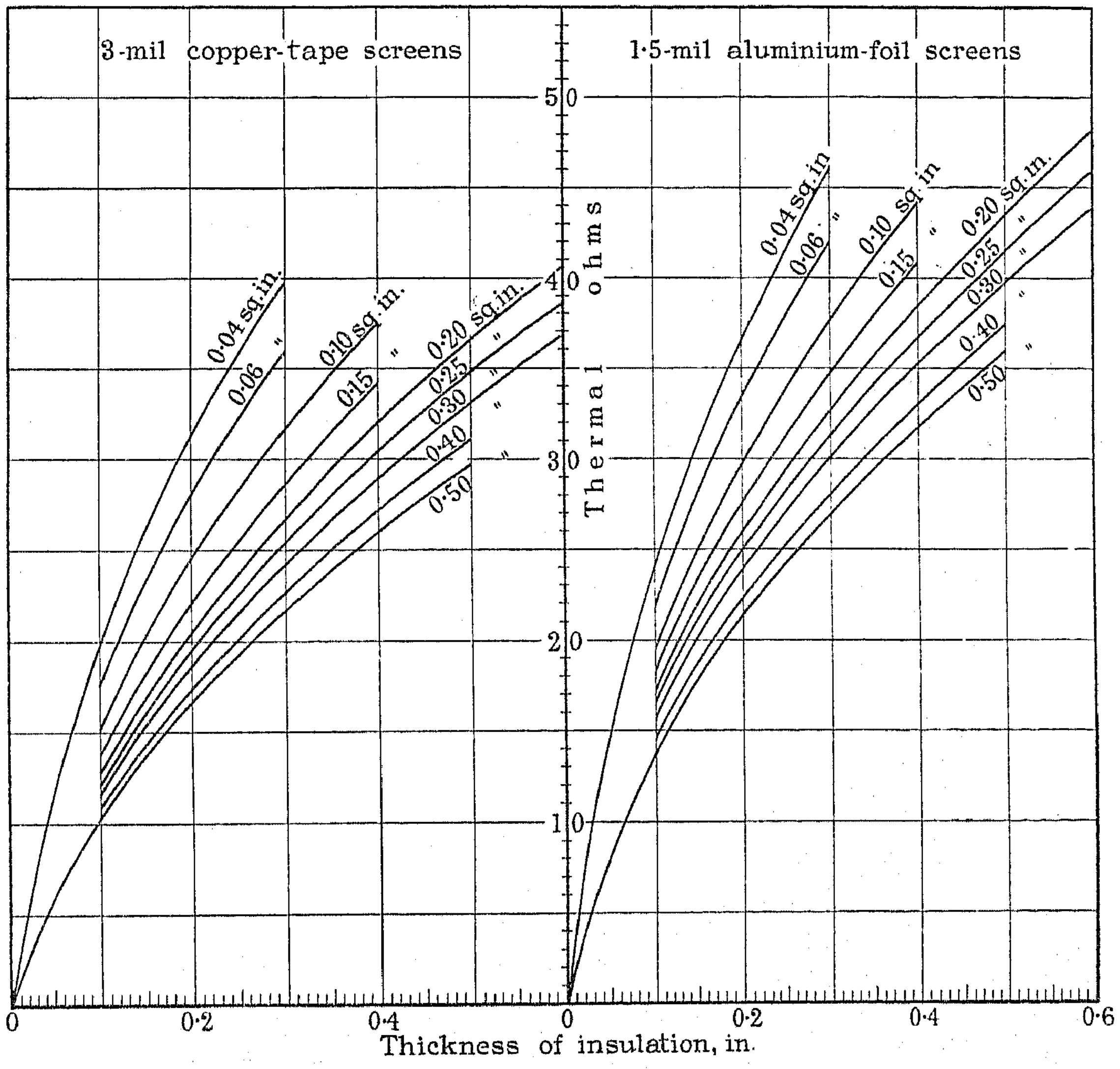


Fig. 8.—Chart showing thermal resistance of 3-core cables with 1·5-mil aluminium-foil screens and 3-mil copper-tape screens ($K = 550$).

### (8) Cables with Shaped Conductors.

The results obtained above refer particularly to the case of cables with circular conductors. The use of sector-shaped or oval-shaped conductors leads to a further improvement in the thermal properties of the cable; this is due to two reasons: (i) The reduction in the thermal resistance between conductors and screens. (ii) More important still, the fact that the screens have a greatly increased arc of contact with the sheath as compared with the screens on circular conductors. A measurement of this arc on actual cable sections shows that with shaped conductors it may subtend an angle of 80° to 100° at the core centre. The effect of this arc of contact in tending to equalize the temperature-drop in the screens, and the consequent reduction in the thermal resistance of the cable, is probably more important in the case of aluminium-foil screens than in the case of copper-tape screens.

Another way of looking at the matter is as follows. With isothermal screens the reduction in thermal resistance would be small, say of the order of 5 per cent only. With infinite circumferential screen resistance the reduction might amount to 20 or 30 per cent. For the particular case of screens with finite conductivity the condition is intermediate, i.e. there is a reduction in thermal resistance, the magnitude of this reduction being greater as the screen circumferential resistance increases.

The general effect would be, therefore, to lower slightly and at the same time to flatten out the experimental curves given in Fig. 5, thus reducing somewhat the discrepancy between the thermal resistances of copper-tape and aluminium-foil screened cables.

It should not be forgotten that the use of shaped conductors involves an increase in the external thermal resistance of the cable due to the smaller overall diameter. Hence the permissible increase of rating as compared with circular-conductor cables may be negligible.

## (9) THERMAL RESISTANCE OF S.L.-TYPE CABLES.

The S.L. type of cable is virtually an assembly of three separately lead-covered cores laid up with packings to circular formation and wrapped with various layers of material for taking the armouring and overall serving. So far, no satisfactory method of calculating the thermal resistance of this type appears to have been developed, but a solution is possible if the lead sheaths and armouring may be regarded as isothermal surfaces. In this case the thermal resistance between conductors and sheaths can be calculated by the usual logarithmic formula, and the thermal resistance between sheaths and armouring determined (as shown below) on the basis of the same heat-flow distribution in the fillers as that previously assumed in the case of screened cables.

In Section (5) it was shown that the temperature-drop in the screens of a 100-mil lead-screened cable is quite small. The case of an S.L. cable, however, is not quite analogous to that of a screened cable from a thermal point of view, inasmuch as the lead sheaths of the former cable are not in actual contact with a circumscribing isothermal surface and this results in a further reduction of temperature-drop round the cores. A typical arrangement is shown in Fig. 9, which represents a 60° sector of an S.L.-type cable with a belt of one cotton and two hessian tapes, having a total thickness of 0·15 in., between the lead sheaths and the armouring. The introduction of a belt of such material, having a comparatively high thermal resistivity, between the sheaths and the isothermal surface formed by the armouring, has an important influence in equalizing the temperature distribution in the sheaths. There is no doubt that for all practical purposes these sheaths are isothermal surfaces.

Consider now that portion of the heat path between the sheaths and the armouring. The filler is assumed to be divided into the same series of slices as before, but this time the lines Xd, Xe, etc., are produced to meet the armouring at the points *d'*, *e'*, etc., as shown in Fig. 9.

The resistances of the filler slices bounded by *cd*, *de*, etc., do not vary with the physical dimensions of the cable and can be readily determined in the way previously described. The resistances of the belt-material slices *cc'd'd*, *dd'e'e*, etc., although dependent on the dimensions of the belt layer, can be readily calculated for any particular case. Hence the resistances of the slices bounded by *c'd'*, *d'e'*, etc., can be ascertained, and by combining these in parallel the total thermal resistance between sheaths and armouring is obtained. The method is best illustrated by means of a practical example.

Take, for instance, the case of a 25 000-volt 3-core S.L.-type 0·20-sq. in. cable having the dimensions shown in Fig. 9. The first operation is to determine the thermal resistance of the belt material, which, for a thermal resistivity of 550, is

$$\frac{6 \times 550}{2\pi} \log_e \frac{1 \cdot 675}{1 \cdot 525}$$
$$= 49 \cdot 7 \text{ thermal ohms (for the } 60^\circ \text{ sector).}$$

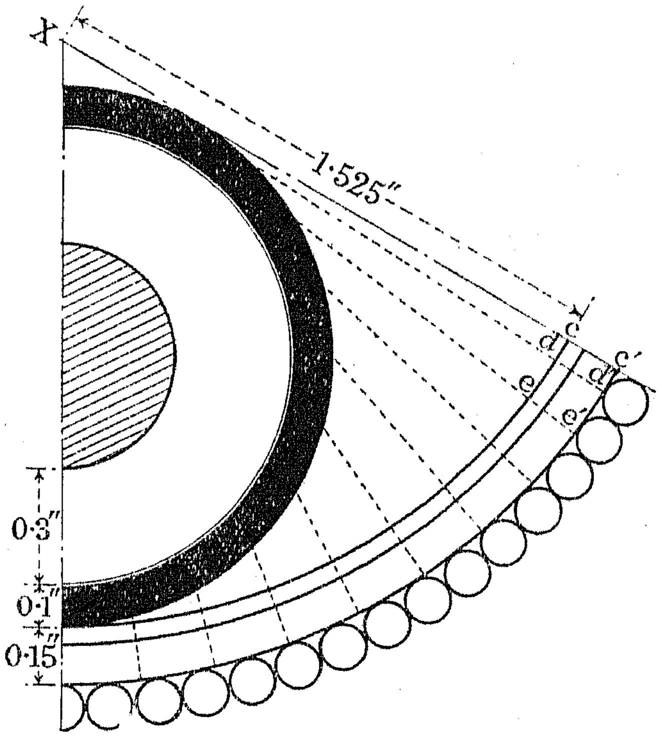
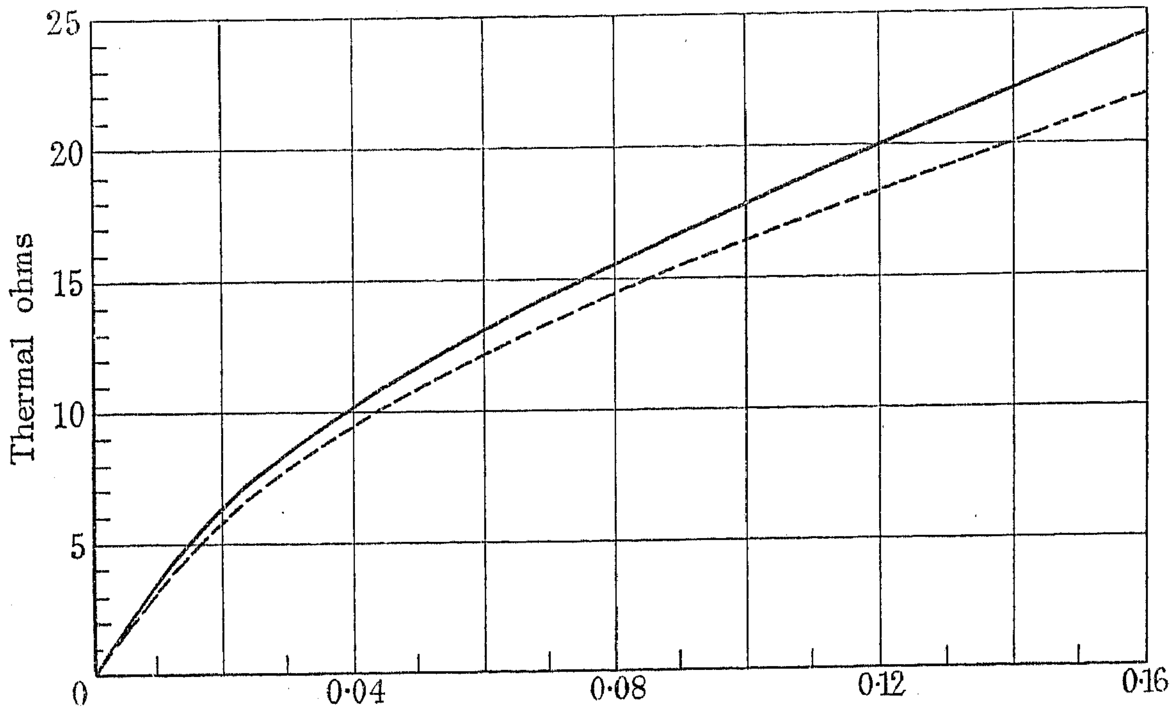


FIG. 9.—60° sector of 25 000-volt 3-core 0·20-sq. in. S.L.-type cable.

The thermal resistance of each of the belt-material slices is inversely proportional to the lengths of the arcs *cd*, *de*, etc., cut off on the circle circumscribing the lead sheaths. The actual lengths of these arcs (see Table 2, Appendix) were measured on a large-scale drawing and are given in the first column of Table 1 as a fraction of the sum total. By dividing the value of the thermal resistance of the belt material (49·7) by each of the figures in col. 1 we obtain, therefore, the actual resistance of each of the slices; these values are given in col. 2. In col. 3 are given the resistances of each of the filler slices, also on a thermal-resistivity basis of 550 (see Table 2, Appendix), and the addition of the values in cols. 2 and 3 gives (in col. 4) the resistance of each of the slices between the two isothermal surfaces.

By transforming to conductances in col. 5, and adding, the total conductance between lead sheaths and armouring for the complete cable is found as 0·008916 × 6 = 0·05350 thermal mho, corresponding to a thermal resistance for this particular case of 18·7 thermal ohms.



Thickness of material between sheaths and armour, expressed as a fraction of sheath diameter.

FIG. 10.—Thermal resistance between sheaths and armour in 3-core S.L.-type cable. (Thermal resistivity of material = 550.)

——— All material wrapped overall (i.e. sheaths in contact).

– – – Equal thicknesses of material between sheaths and between sheaths and armour.

The thermal resistance of the cable between conductors and sheaths is

$$S_c = \frac{550}{6\pi} \log_e \frac{R}{r}$$

$$= \frac{550}{6\pi} \log_e \frac{0\cdot 59}{0\cdot 29} = 20\cdot 8 \text{ thermal ohms}$$

so that the total thermal resistance of the cable between conductors and armouring is $18\cdot 7 + 20\cdot 8 = 39\cdot 5$ thermal ohms.

The value of 39·5 thermal ohms for the S.L.-type cable should be compared with the corresponding values of 26·7 for a screened cable with 3-mil copper-tape screens, 32·7 for a cable with 1·5-mil aluminium-foil screens, and 41·1 for an unscreened cable.

The general convenience of the above method of determining the thermal resistance of the path between sheaths and armouring arises from the fact that the ratios given in the first column of Table 1 are valid no matter what the physical dimensions of the belt material. The belt-material thermal resistance for any practical case having, therefore, been calculated, these ratios can be applied direct to obtain the resistance of each of the belt-material slices. The actual values of these resistances shown in col. 2 have been obtained on the basis of a belt-material thermal resistance for the 60° sector of 49·7 thermal ohms; so that, if the actual calculated value in another case is $S'$, it is only necessary to multiply the figures in col. 2 by $S'/49\cdot 7$ to obtain the individual slice-resistances for this case. These values can then be combined as shown in the above example.

Working on these lines, Fig. 10 has been prepared, the upper curve in this diagram showing the thermal resistance between sheaths and armouring for different ratios of belt-material thickness to sheath diameter. In deriving this curve it has been assumed that both the belt material and fillers have a thermal resistivity of 550, but variations in the thermal resistivity of either or both of these materials can be allowed for without difficulty.

So far in the treatment of the subject the three lead sheaths of the cable have been assumed to be in actual contact. There is another type of "S.L." cable in use, however, in which each lead sheath is separately wrapped before being packed to circular formation and the overall wrapping applied. Assuming equal thicknesses of core

TABLE 1.

*Determination of Thermal Resistance of S.L.-Type Cable shown in Fig. 9 between Sheaths and Armouring ($K = 550$).*

| Relative lengths of arcs | Extra thermal resistance due to belt material | Thermal resistance of filler slices | Total thermal resistance of slices | Thermal conductance of slices |
|---|---|---|---|---|
| | Thermal ohms | Thermal ohms | Thermal ohms | Thermal mho |
| 0·0399 | 1 240 | 13 000 | 14 240 | 0·000070 |
| 0·0785 | 630 | 5 030 | 5 660 | 0·000177 |
| 0·0965 | 510 | 3 070 | 3 580 | 0·000279 |
| 0·1037 | 480 | 2 040 | 2 520 | 0·000397 |
| 0·1092 | 460 | 1 350 | 1 810 | 0·000552 |
| 0·1116 | 450 | 860 | 1 310 | 0·000764 |
| 0·1136 | 440 | 500 | 940 | 0·001063 |
| 0·1148 | 430 | 250 | 680 | 0·001470 |
| 0·1160 | 430 | 90 | 520 | 0·001922 |
| 0·1162 | 430 | 20 | 450 | 0·002222 |
| Total conductance of 60° cable sector = | | | | 0·008916 |

and overall wrapping, the thermal resistance between sheaths and armour in this case can be derived from Simons's geometric factor curves. Thermal-resistance values between sheaths and armouring obtained by this means are shown in the lower curve of Fig. 10. It will be seen from a comparison of the two curves that the relative thicknesses of core and overall wrappings have little influence on the thermal resistance.

A general comparison between the thermal characteristics of S.L. and other types of 3-core cables is rendered difficult owing to non-standardization of make-up over the lead sheaths in the case of the former type. Various materials are in use for packing and wrapping the lead-sheathed cores prior to armouring, and reliable data on the thermal properties of some of these materials are lacking. There is no reason, however, for thinking that the assumed value of 550 for the thermal resistivity of this material is too high, and on this basis it is evident that the thermal resistances between sheaths and armouring may have a substantial value. It appears, therefore, that the thermal resistance of an S.L.-type cable may often be distinctly higher than that of a screened cable.

## (10) CONCLUSIONS.

Experimental work with electrical networks set up to represent the heat paths in screened-type cables shows that the effect of the screens is to reduce the thermal resistance between conductors and sheath very considerably. Over the practical range of cable sizes, cables with 3-mil copper-tape screens have a thermal resistance of 58 per cent to 70 per cent, and 1·5-mil aluminium-foil screened cables 70 per cent to 84 per cent, of the thermal resistance of an unscreened cable having the same dimensions. These figures are in substantial agreement with those obtained by Konstantinowsky and Tschiassny using an electrolytic method, and also with the results obtained by the method of calculation suggested by Beavis.

In the S.L.-type cable the sheaths are sensibly isothermal and, taking advantage of this fact, the thermal resistance between conductors and armouring can be obtained by a semi-graphical method. Owing to non-standardization of finish over the lead sheaths, an accurate comparison between the thermal resistances of S.L. and other types of 3-core cables is not possible. Investigation of the possible limits of variation, however, seems to show that in some cases the thermal characteristics of S.L. cables may be somewhat inferior to those of screened cables.

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(1) D. M. SIMONS: "Calculation of Current-Carrying Capacity of Type-H Cable," *Electric Journal*, 1926, vol. 23, p. 59.

(2) E. A. BEAVIS: "Thermal Resistance of E.H.T. Cables," *Electrical Times*, 1931, vol. 80, p. 201.

(3) D. M. SIMONS: "Cable Geometry and the Calculation of Current-Carrying Capacity," *Transactions of the American I.E.E.*, 1923, vol. 42, p. 600.

(4) K. KONSTANTINOWSKY and L. TSCHIASSNY: "A New Type of Cable," Report of the International E.H.T. Conference, 1927, vol. 1, p. 796.

(5) L. TSCHIASSNY: "The Heat-Dissipation Conditions in Three-Core Cables of Non-Circular Cross-Section," *Archiv für Elektrotechnik*, 1931, vol. 25, p. 459.

## APPENDIX.

Referring to Fig. 3, bare eureka wires of No. 38 S.W.G. were used to represent the thermal resistance of the core sectors, and as the maximum length available for these wires on the apparatus was 57 in. this length represented the highest $t_c/d$ to be covered by the experiments, viz. 1·0. For this ratio each of the core sectors has a thermal resistance of $[24 \times 550/(2\pi)] \log_e 3\cdot0 = 2\,309$ thermal ohms. As the average electrical resistance of each of the twelve wires is 38·31 ohms a measurement of 1 ohm on the apparatus corresponds to a thermal resistance of $2\,309/38\cdot31 = 60\cdot27$ thermal ohms.

The resistances representing the screen-element thermal resistances were bare eureka wires of No. 18 S.W.G. about 140 in. long. The ratio between the resistances of the No. 38 S.W.G. and No. 18 S.W.G. wires was measured and found to be 63·4. Hence 140 in. of the No. 18 S.W.G. wire corresponds to a thermal resistance of $(2\,309 \times 140)/(57 \times 63\cdot4) = 89\cdot43$ thermal ohms, thus providing for measurements with 1-mil aluminium-foil screens up to a maximum core diameter of 1·46 in. This would correspond to an overall cable diameter of about 4 in.

TABLE 2.

*Determination of Thermal Resistance of Filler Slices* ($K = 550$).

| Number of slices | Average length | Average width | Length of arc | Thermal resistance |
|---|---|---|---|---|
| | in. | in. | in. | Thermal ohms |
| 1 | 15·73 | 0·665 | 1·00 | 13 000 |
| 2 | 13·08 | 1·43 | 1·97 | 5 030 |
| 3 | 10·50 | 1·88 | 2·42 | 3 070 |
| 4 | 8·03 | 2·16 | 2·60 | 2 040 |
| 5 | 5·88 | 2·40 | 2·74 | 1 350 |
| 6 | 4·00 | 2·56 | 2·80 | 860 |
| 7 | 2·46 | 2·70 | 2·85 | 500 |
| 8 | 1·28 | 2·80 | 2·88 | 250 |
| 9 | 0·48 | 2·87 | 2·91 | 90 |
| 10 | 0·09 | 2·88 | 2·92 | 20 |

The filler resistances were obtained to a sufficient degree of accuracy by drawing a large-scale cable sector, the diameter of the circle circumscribing the cores being 47·8 in., and measuring the average lengths and widths of each slice. The results are given in Table 2, the thermal resistances of the slices being represented on the apparatus, according to their magnitude, by No. 38 S.W.G. or No. 18 S.W.G. insulated eureka wire.

When carrying out the measurements, in order to convert readings of electrical resistance taken on the apparatus into corresponding values of thermal resistance for the complete cable, it is necessary to multiply by the factor 10·04. The conversion factor 60·27 given above applies particularly to the case of a 60° sector.

# THE DEVELOPMENT OF A SENSITIVE PRECISION WATTMETER FOR THE MEASUREMENT OF VERY SMALL POWERS.*

By N. HALIFAX SEARBY, Ph.D.

(*Paper first received* 21*st September*, 1933, *and in final form* 9*th August*, 1934.)

## SUMMARY.

The need and requirements for a wattmeter suitable for the measurement of iron losses, and capable of measuring powers of the order of 0·1 watt at low power factors with an accuracy of at least 1 per cent, are discussed.

The principle of the suggested instrument is given, and the various errors likely to occur and methods of eliminating them are reviewed. The factors governing the design, and the method of design, follow. The results of seven designs are tabulated, the best being chosen. Finally the details and results are given of the tests carried out on a completed instrument.

## LIST OF SYMBOLS.

$A$ = area of moving coil.
$B$ = flux density.
$C$ = capacitance of condenser for power-factor error correction.
$E$ = voltage to be measured or applied to instrument.
$I$ = current to be measured or applied to instrument.
$I_1$ = direct current in current circuit.
$I_2$ = direct current in voltage circuit.
$i_1$ = instantaneous alternating current in current circuit.
$i_2$ = instantaneous alternating current in voltage circuit.
$K_1, K_2, K_3, K_4$ = constants.
$L$ = inductance of current circuit.
$L_f$ = inductance of fixed coil.
$L_m$ = inductance of moving coil.
$L_p$ = inductance of voltage circuit.
$M$ = mutual inductance between fixed and moving coils.
$M_0$ = mutual inductance between fixed coil of one and moving coil of other system.
$N_1$ = turns on fixed coil.
$N_2$ = turns on moving coil.
$P'$ = power indicated by wattmeter.
$R_a$ = added resistance of voltage circuit.
$R_c$ = copper resistance of voltage circuit.
$R_i$ = resistance of current circuit.
$R_p$ = resistance of voltage circuit.
$\mathbf{T}$ = torque in dynamometer.
$\mathbf{T}_a$ = torque due to alternating current applied.
$\mathbf{T}_d$ = torque due to alternating currents induced in d.c. dynamometer.
$X_p$ = reactance of voltage circuit.

## LIST OF SYMBOLS—*continued.*

$Z_i$ = impedance of current circuit.
$\beta$ = complement of angle between fixed and moving coils.
$\Phi$ = total flux produced by current coils.
$\Phi_2$ = flux through an area $A$.
$\phi$ = phase angle between $E$ and $I$.
$\omega = 2\pi \times$ frequency.

## INTRODUCTION.

It has long been felt that the methods at present in use for the commercial measurement of iron losses in small transformer cores and samples of electrical sheet steel leave much to be desired.

Briefly, of these, the following are in general use.

### (*a*) *Epstein Square and Wattmeter.*

This method is by far the most common, but it has the serious disadvantage that, even when it is used with the best indicating wattmeter available, readings at as low a value of $B$ as 6 000 lines per $cm^2$ cannot be guaranteed to nearer than 5 per cent with 10 kg of iron. The chief obstacle in the way of greater accuracy is the low power factor, since, even if the wattmeter is used at its full volt-amperes, only a small part of full-scale reading is obtained.

For commercial purposes, in tests on sheet steel, a value of the iron loss per lb. is usually required at $B$ = 10 000 lines per $cm^2$. At this density the Epstein-square method can be reasonably accurate if 10 kg of iron are used for each test.

In a large works producing 100 batches of sheets per week, the making of a test on each batch would mean nearly 5 tons of scrap sheet per month. This is, presumably, the main reason why tests are not regularly carried out in the course of manufacture and why the uniformity of quality which characterizes most other electrical manufactures has not yet been obtained in electrical steel.

The Epstein-square method is quite convenient; and save for the fact that with ordinary wattmeters 10 kg of iron must be used, it would be satisfactory commercially.

### (*b*) *Bridge Methods.*

These are not in such general use as the wattmeter method, and though good from a scientific point of view they are, from a commercial point of view, too cumbersome.

Expensive subsidiary apparatus is required, e.g. a vibration galvanometer, a standard variable inductance, and non-inductive resistance boxes. These, for the best sensitivity, must all be able to carry the current required in the windings on the sample. This current must be rather above the usual "bridge" currents, unless a great number of turns is used, which makes the winding of a small ring sample very troublesome; so troublesome, in fact, as more than to offset the advantage gained by the use of a small weight of iron.

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The tests are also, for commercial purposes, limited to a fixed frequency on account of the difficulty of obtaining a vibration galvanometer to work satisfactorily over a wide range of frequencies. A sinusoidal supply is also essential for good results.

### (*c*) *Potentiometer Methods.*

(i) *Drysdale potentiometer.*—This can be used on small samples, but requires the same vibration galvanometer and virtually fixed frequency as do the bridge methods. In this method we read $E$, $I$, and $\phi$. Great inaccuracies may occur owing to error in $\phi$, since at $\phi = 88°$ an error of $\frac{1}{2}°$ (which is quite possible) causes an error of 25 per cent in the watts. The Drysdale potentiometer is not suitable for measurements at low power factors.

(ii) *Gall co-ordinate potentiometer.*—Here we have a method which has a sound basis for low power factor working, since the two components of each vector ($E$ and $I$) are obtained. From a scientific point of view it appears that excellent results can be obtained in iron-loss and permeability measurements, with, however, the tiresome manipulation attendant on all a.c. bridge and potentiometer methods using a vibration galvanometer. Such an apparatus is very useful for scientific and research work but is not very suitable for commercial purposes.

Reviewing the three methods, it appears that method (*a*) is still the most suitable for works use. If a wattmeter could be devised with a sensitivity at least 100 times that of the most sensitive indicating instruments, it would be possible to carry out satisfactory tests on 100 g or so of iron by the quick wattmeter method. With such an object in view, the author set to work on the instrument which will be described later in the paper.

## GENERAL REQUIREMENTS.

The essential features of a wattmeter suitable for the purpose mentioned above are as follows.

(1) It should be capable of testing small weights of iron (say, 100 g at $B = 10\,000$ lines per cm$^2$). This means that $0 \cdot 1$ watt should be easily measurable.

(2) No great error must be introduced at low power factors (say, $\cos \phi = 0 \cdot 05$).

(3) In order to cover the range of values of $B$ which may be desired, and to keep the number of turns on the ring or other sample low, it is convenient to wind samples with wire of about No. 18 S.W.G. and to work at fairly high currents with low voltages. Thus the instrument should be designed for low voltages and fairly heavy currents; for example, 4 volts (maximum on lowest range) and 10 or 20 amps.

(4) The instrument should read the watts lost in the sample directly and should therefore be compensated for any loss in its own windings.

(5) The instrument must be easy and quick to manipulate.

(6) Greater accuracy than that of British Standard 1st grade or sub-standard instruments is not desirable, since, in general, supersensitivity means tiresome manipulation. As regards accuracy, for most purposes 5 per cent would be sufficient in general commercial testing, but, since it would be very desirable for the uniformity in quality of sheets not only to be checked to 5 per cent but also to be improved, it would not be too much to say that an accuracy of within 1 per cent should be required in the measurement of, say, $0 \cdot 1$ watt. It is hoped that if manufacturers possessed a suitable instrument easily capable of measuring within 1 per cent, then it would not be long before their steel could be produced to this degree of uniformity.

(7) It should be possible to use the instrument over a wide range of frequencies without introducing serious error.

(8) A portable instrument is not required, but the apparatus should be so designed that it can be readily set up, and it should require neither any elaborate pier or anti-vibration device nor complicated subsidiary apparatus. It should be robust (i.e. capable of transport without damage).

(9) It should be small and relatively inexpensive.

(10) It should not require to be referred to any other standard apparatus for calibration.

(11) As wide a range of applicability as possible should be obtained.

## PRINCIPLE OF THE INSTRUMENT.

By using the following principle, which was suggested to the author by Mr. E. J. Kipps, it was found possible to construct an instrument which satisfies all the foregoing requirements.

The moving coils of two identical dynamometers are mounted on the same spindle one above and at right angles to the other, using a suspension with mirror, lamp, and scale. The moving system is set to a zero with the fixed and the moving coils mutually at right angles. One dynamometer is connected to the a.c. load to be measured, and the other to a d.c. supply. Adjusting the direct current until the torques of the two systems are exactly opposed, and measuring the d.c. volt-amperes, we say that these are equal to the a.c. watts.

That such a principle is sound cannot be doubted, provided that: (*a*) The two dynamometers are adjusted so as to give identical torques with the same d.c. voltage and current applied to each. (*b*) The dynamometers are designed so that the errors in the torque on alternating current as compared with the torque on direct current are within the required limits. (*c*) It is possible so to arrange the two dynamometers that one has no effect upon the other.

### *Means of Satisfying the Requirements.*

The above requirements are satisfied by the following methods:—

(1) By the employment of the suspension and reflecting features great sensitivity will be secured.

(2) By keeping the inductance of the moving coils low, using a few turns of small diameter. (This will also satisfy requirement 3, since low inductance will permit low voltages.)

(4) By means of compensating windings wound with the fixed coils and connected in series with the voltage coils.

(5) By keeping the period of oscillation low and the damping fairly heavy, and by measuring the d.c. volts and amperes on sub-standard moving-coil indicating instruments.

(6) So long as the instrument be made to an accuracy well beyond that of the d.c. moving-coil instruments used for measuring the watts, requirement (6) will be satisfied. Referring to a series of tests given by Drysdale and Jolley,* it appears that an accuracy greater than 0·5 per cent could not be expected in the d.c. watts, even if the instruments were always used above half-scale. It therefore follows that, even for commercial purposes, the instrument should be made so that no individual error exceeds 0·1 per cent. In this case, in the event of several errors adding, an error of, say, 0·3 per cent could occur, which could be in the same direction as the 0·5 per cent error in the d.c. watts. It is thus essential that, for 1 per cent final accuracy, no one error should exceed 0·1 per cent. If, on the most sensitive range, the instrument were designed for a maximum voltage of 4 volts and a maximum current of 10 amps., and a sensitivity were obtained such that the instrument could be balanced to 0·0005 watt (all other errors being kept within 0·1 per cent), clearly we could measure between 0·0005 watt and 40 watts (unity power factor) with varying degrees of accuracy. From 0·1 watt to 40 watts (unity power factor) the accuracy would be as good as the d.c. instruments allow. Below 0·1 watt we could only measure to the nearest 0·0005 watt, and hence at 0·01 watt the error could be 5 per cent and the accuracy of the d.c. instruments would exceed that of the wattmeter. In this case all other errors would be insignificant.

(7) A dynamometer instrument, carefully designed, avoiding the use of metal near the coils and keeping the inductance of the voltage circuit very low compared with its resistance, should be reasonably accurate even at frequencies well into the audio-frequency range, say 1 000 cycles per sec.

(8) This requirement conflicts with the desire for great sensitivity. In satisfying it, therefore, the best we can do is to make the instrument no more sensitive than is required for the object in view. We have decided that the instrument will be satisfactory if it can detect 0·0005 watt. Even if greater sensitivity could be obtained, it would be disadvantageous to make use of it, since the instrument would then be more fragile than it need be. As regards subsidiary apparatus, only a 4-volt storage battery, regulating resistances, and two good d.c. instruments, will be required.

(9) This and requirement (2) assist each other, since small inductance will mean small coils and few turns. The subsidiary requirements are so modest that their expense will not be great.

(10) Since the instrument will employ a null method, it will be self-checking. The only calibration required will be that with the same direct current applied to both movements; one must be adjusted so that its torque exactly opposes that of the other. Provided the zero position be maintained no further calibration is required and either dynamometer may be used as the a.c. system. As will be seen later, it was found better in practice to use the top movement for alternating current and the bottom one for direct current.

(11) By providing several voltage and current ranges. This should be done as simply as possible, since if elaborate commutator devices be used the expense may prove too great. It was considered that simple series-parallel connection for current coils giving current ranges of 10 and 20 amperes and, say, five ranges for the voltages from 4 to 300 volts, would be sufficient.

## ADVANTAGES OF THE A.C./D.C. BALANCE TYPE OF SUSPENSION DYNAMOMETER AS COMPARED WITH TORSION-HEAD AND INDICATING INSTRUMENTS.

Many great advantages will already be obvious from the foregoing remarks: in addition to these it will be well to note also some of the less apparent.

(*a*) The fact that a null method is employed gives the following advantages.

(i) Greatly extended range. The range 0·1 watt to 40 watts on one instrument with the accuracy of moving-coil instruments above half-scale is exceptional. Still greater range may be obtained by using shunts and series resistances.

(ii) The moving coils are always in the position of maximum sensitivity.

(iii) The coils are always in the position of zero mutual inductance. There will therefore be no mutual inductance errors in either instrument.

(iv) The suspension is not an important part of the instrument. Its exact torsional characteristics do not matter.

(v) The instrument is self-checking.

(vi) The levelling of the instrument is not vital, since the self-checking is so readily performed if the instrument is moved.

(vii) A torsion head is avoided; in its place there is substituted a d.c. control which is operated without the necessity for touching the instrument.

(*b*) When fairly large torques are being balanced the oscillations of the moving system will be reduced, since the restoring force of the suspension will be small compared with the two opposing torques due to the a.c. and d.c. watts respectively. Thus, except to a small degree, there will really be no oscillating system. This should make for ease of manipulation.

With these preliminary remarks as to the requirements and general lines on which such an instrument should be constructed, we may proceed to a brief consideration of the errors which are likely to occur and of the methods by which they may be overcome.

## ERRORS, AND METHODS BY WHICH THEY MAY BE OVERCOME.

### (*a*) *Self-inductance of Voltage Circuit.*

This error only occurs in the a.c. instrument. It is easy to show that a dynamometer reads

$$P' = EI\left[\cos\phi + (X_p \sin\phi/R_p)\right]$$
$$= \text{True watts} + (EIX_p \sin\phi/R_p)$$

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* "Electrical Measuring Instruments," part 1, p. 256.

where $\phi$ = true phase angle of load, and $X_p$ and $R_p$ are respectively the reactance and resistance of the voltage circuit. At zero power factor the instrument reads $EIX_p/R_p$, since $\sin\phi = 1$. Thus the actual error in the power factor at zero power factor is equal to $X_p/R_p$.

The error occurring at zero power factor will not be exceeded at any other power factor. Therefore we may say that at and near zero power factor the error in power factor is $X_p/R_p$. If this error is not to exceed, say, 0·001, then $X_p/R_p = 0{\cdot}001$, or $R_p = 314$ ohms per mH of inductance at a frequency of 50 cycles per sec.

It was therefore decided to use a series resistance of 314 ohms per mH. The error may be decreased by (i) decreasing $X_p$, (ii) increasing $R_p$. The former is the best course to adopt, since (ii) also decreases the sensitivity.

Method (i) may be applied by using a small moving coil of few turns and/or shunting the series resistance of 314 ohms per mH with a suitable condenser. In the latter case, for perfect correction, the capacitance of the condenser must be $C = L_p/R_p^2$, where $L_p$ is the inductance of the voltage circuit. This is correct at all frequencies, with the exception of those which are high enough to make $\omega^2C^2R_p^2$ comparable with unity. In the actual wattmeter constructed by the author, at 5 000 cycles per sec. the error would still be corrected within 2 per cent.

For the series resistance the asbestos woven type was used since, according to Drysdale and Jolley,* this is the most perfect form of non-inductive resistance available.

### (*b*) *Eddy Currents due to the Current Coils.*

These, if they exist, have the effect of partly compensating or even over-compensating, over a wide range of frequencies, the error due to inductance in the voltage circuit, since they cause the flux of the current coils to lag slightly behind the current.

It was thought better, however, to avoid eddy currents rather than to use them to correct errors due to the self-inductance of the voltage circuit. In tests carried out by the author on air-cored magnetizing coils wound with wires for 15 amperes, at 1 000 cycles per sec. it was found that eddy currents were reduced to a negligible value if stranded wire of the ordinary flexible type (not litzendraht) were used.

Thus if we use such wire and avoid, as far as possible, the use of metal in the frame and case, the instrument will certainly be accurate in this respect up to, say, 1 000 cycles per sec.

### (*c*) *Wave-form.*

A dynamometer designed so as to give correct indication up to, say, 1 000 cycles per sec., will indicate correctly the true power of the fundamental and any harmonic likely to occur in a commercial-frequency supply. The instrument will therefore read the true power of any such wave provided that the harmonics occur in both current and voltage waves.

### (*d*) *Effect of the Earth's Field.*

It was decided not to make the instrument astatic, but to preserve the full torque of the simple dynamometer and provide a coil wound outside the current coils and connected to an adjustable d.c. supply (2-volt accumulator and resistance). The current in this coil could be adjusted so that its flux would exactly neutralize the axial component of the earth's field. Coils must be provided on both dynamometers for use when checking the instrument with direct current in both movements.

It is now felt that it would probably be better, even at some sacrifice of sensitivity, to make the instrument astatic for use in a works laboratory, since this course also protects against stray a.c. fields whereas the course adopted by the author does not.

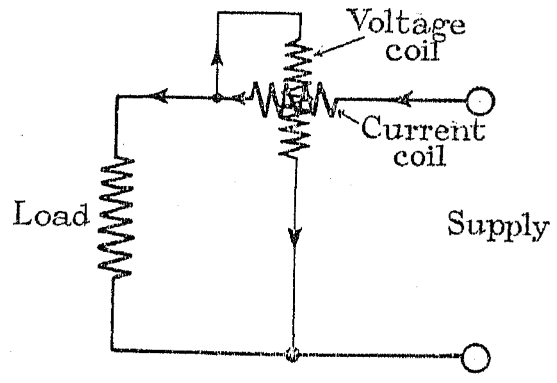

FIG. 1.

### (*e*) *Loss in the Voltage Circuit.*

If the instrument is connected to its load as in Fig. 1, the current in the voltage circuit, in addition to the main current, passes through the current coils and produces a torque just as does a dynamometer voltmeter. To compensate this error, the method used by the Weston Co. and indicated in Fig. 2 was employed.

Along with the current coils, a winding of thin wire (for voltage-circuit current) is wound, side by side. This winding is connected in series with the voltage circuit and has the same number of turns as the current coils. It is supposed to produce a flux equal and opposite to that produced by the voltage-circuit current flowing in the current coils. In practice, however, the compensating turns are wound on a smaller radius than the current coils and so do not compensate exactly. Exact compensation was nevertheless obtained, when the instrument was completed, by shunting the compensating circuits with fairly high resistances, the values of which were obtained on test. If compensation is used, the voltage circuit must be connected to the side of the current coil nearest to the load.

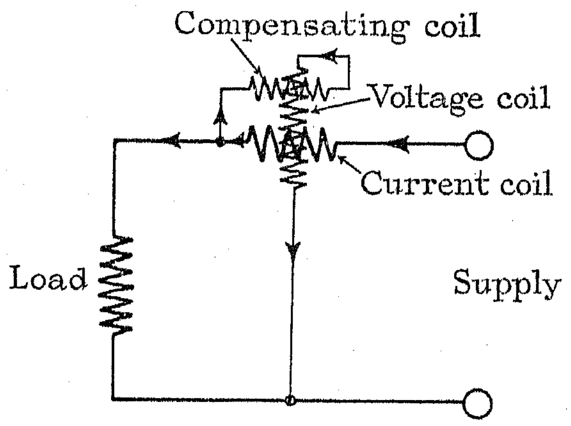

FIG. 2.

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* "Electrical Measuring Instruments," part 1, p. 316.

### (*f*) *Effect of One Dynamometer on the Other.*

Referring to Fig. 3, the field from the a.c. fixed coil cuts the d.c. moving coil. This coil, having a closed circuit through the battery supplying it, will have a small alternating current induced in it. Similarly, the a.c. moving coil will induce a small alternating current in the d.c. fixed coil. There will be no resultant torque between the a.c. fixed coil and the d.c. moving coil or the a.c. moving coil and the d.c. fixed coil on this account, since the axes of the coils are parallel and the torque is given by

$$\mathbf{T} = i_1 i_2 \frac{dM}{d\beta}$$

As the coils have parallel axes, $M$ is a maximum; hence $dM/d\beta = 0$, and no torque is exerted. We should, however, expect the interaction of the two alternating currents induced in the d.c. coils to produce some torque, albeit small.

If $\mathbf{T}_a$ = whole torque of one dynamometer, proportional to $EI$ (d.c.), and $\mathbf{T}_d$ = torque in d.c. dynamometer due to alternating current in the a.c. system, it is easy to show that

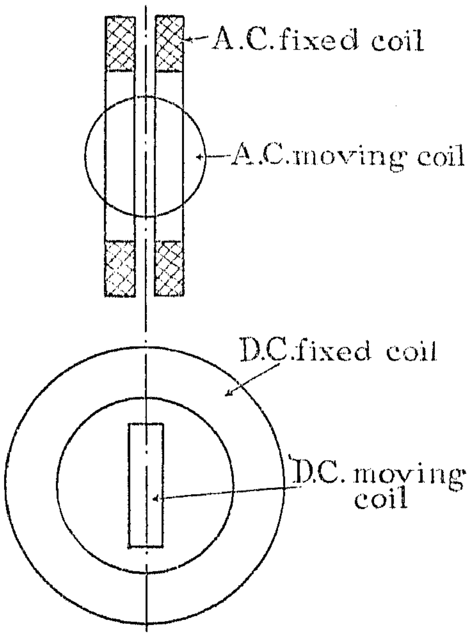

FIG. 3.

$$\frac{\mathbf{T}_d}{\mathbf{T}_a} = \frac{\omega^2 M_0^2}{Z_i R_p}$$

where $M_0$ = coefficient of mutual induction between a fixed coil and the moving coil in the other dynamometer, and $Z_i$ = impedance of current circuit. In the actual instrument $M_0$ was about $0 \cdot 25\ \mu\text{H}$, $Z_i$ not less than 1 ohm, and $R_p$ not less than 40 ohms; hence

$$\frac{\mathbf{T}_d}{\mathbf{T}_a} = \frac{(314)^2 \times (0 \cdot 25)^2}{10^{12} \times 40} = \tfrac{1}{64} \times 10^{-8}, \text{ for 50-cycle supply}$$

Clearly this source of error is entirely negligible.

### (*g*) *Heating of Voltage Circuit.*

The fact that we have a high series resistance of negligible temperature coefficient is advantageous from this point of view. If $R_c$ = copper resistance (including suspension), and $R_a$ = additional resistance (of zero temperature coefficient), then, if $R_a = 7R_c$ and a difference of temperature between the two moving coils of 2 deg. C. is not exceeded, the error will not be greater than $0 \cdot 1$ per cent.

If the moving coils are designed for a maximum temperature-rise not exceeding 3 deg. C., the possibility of a difference of temperature greater than 2 deg. C. between the moving coils is very remote.

### (*h*) *Heating of the Current Coils.*

Since the resistance of the current coils is immaterial, their heating has no direct electrical effect on the accuracy of the instrument. It was found, however, that, even with the small temperature-rise which was allowed for the current coils, the convection air currents rising from them and impinging on the mica damping vanes affixed to the moving coils caused considerable deflections, and in some cases oscillations, of the moving system. To overcome this, draught shields were fitted to enclose the damping vanes. The final effect of current in the fixed coils only will be given later in the paper, along with the experimental results.

### (*j*) *Electrostatic Effects.*

If the fixed and moving coils of either dynamometer are at widely different potentials, a deflection will be produced in the same way as in an electrometer. This effect may be eliminated by correct connection of the fixed and moving coils. This connection is simplified by the fact that the instrument is compensated and must, in any case, always be connected in a definite way.

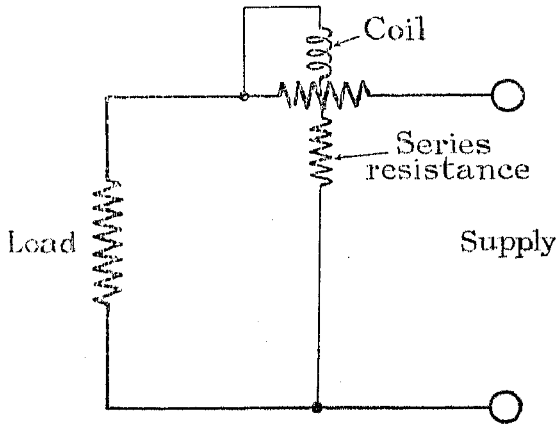

FIG. 4.

If the moving coil and series resistance are connected as shown in Fig. 4, no difference of potential exceeding a fraction of a volt can occur between the fixed and moving coils.

### (*k*) *Thermo-electric Effects.*

These can only arise in the voltage circuit with its series resistance, since the current coils have no shunts.

In practice,* however, in voltmeters, with their high-resistance circuits, thermo-electric errors are not appreciable. It is safe to assume that no serious errors of this sort will occur in the voltage circuit.

### (*l*) *Lack of Balance between the Two Dynamometers.*

This may arise from four main causes: (i) Dissimilarity between the current coils. (ii) Dissimilarity between the voltage coils. (iii) Unequal resistances of the voltage circuits. (iv) Movements not mounted truly at right angles.

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* "Electrical Measuring Instruments," part 1, p. 256. In a whole series of commercial voltmeters tested, no thermo-electric errors could be detected. These, however, were noted for ammeters.

Causes (i) and (ii) cannot be adjusted. The best we can do is to wind the coils on the same former in case (i), and on formers made as nearly identical as possible in case (ii). As regards (iii), the difficulty of making two identical resistances is well known. Little difficulty should be experienced, however, in making the resistances of the two voltage circuits the same to within the limits of accuracy required, i.e. to 1 in 2 000. Cause (iv) will not matter, since a null method is employed.

A method of adjustment which will correct all four effectively is to provide means of moving the two halves of each fixed coil relative to each other. This will vary the field strength inside either coil, and a sufficiently accurate balance should thus be obtained.

## DESIGN.

### *Governing Factors.*

Many factors which govern the design have already been made apparent. The most important of these are: low voltage and moderate currents; minimum self-inductance; compensation for loss in voltage circuit; coils to counteract the earth's field; stranded wire for current coils; avoidance of use of metal other than the coils; low period of oscillation, say 2 sec. (maximum); a sensitivity to detect less than 0·5 mW is not required (greater sensitivity means greater fragility and tiresome manipulation).

In addition to these requirements, we have to come to some decision as to the best shapes and sizes for the coils. It has been shown* in a general way that, for an instrument with a fixed period of oscillation, absolute dimensions probably make little difference to the sensitivity if we neglect all such factors as the weight of the spindle, the inductance of compensating windings, etc.; but in practice such factors are of the utmost importance. It is, however, possible immediately to settle the best shapes for the coils.

### *Shapes of Coils.*

(*a*) *Fixed coils.*—Since the instrument is to be compensated, the inductance of the fixed or current coils is as important as that of the moving coils. We require the shape of coil which will give the maximum flux with the least self-inductance.

Since $L = (N\Phi/I) \times 10^8$, the coil required is that which gives the required flux with the least number of turns. If we utilize $N$ turns in coils of the same diameter, the coil which gives the maximum self-inductance† is a coil of square cross-section. It follows, therefore, that the minimum number of turns to produce the desired flux will be required if a coil of square cross-section is used. The numbers of turns required for a solenoid of 10 cm mean diameter and a coil of square cross-section of the same mean diameter, to produce the same flux, were found to be 18 and 12 respectively.

(*b*) *Moving coils.*—In this case we have

$$\mathbf{T} = I_1 I_2 \frac{dM}{d\beta}$$

where $I_1$ = current in fixed coil, $I_2$ = current in moving coil, $\beta$ = complement of angle between the axes of the coils, $M = (N_2\Phi \sin \beta)/I_1$, and $\Phi$ = total flux cutting the moving coil if it is at right angles to the flux (i.e. total flux passing through an area $A$ equal to the area of the moving coil). Hence

$$\begin{aligned}\mathbf{T} &= I_1 I_2 \frac{d}{d\beta}\left(\frac{N_2\Phi \sin \beta}{I_1}\right) \\ &= I_2 N_2 \Phi \cos \beta\end{aligned}$$

The torque is clearly a maximum when $\beta = 0$, i.e. the coils are at right angles. Thus, for two coils at right angles,

$$\mathbf{T} = I_2 N_2 \Phi$$

Drysdale* shows that, for maximum torque, $\Phi$ should be as large as possible. In addition, the moving coil should be as large as possible compared with the fixed coil; both the coils should be circular, and if the fixed coil is made in two halves these latter should be as close together as possible. No clue is given, however, as to the sizes of coils or even to their cross-sectional shapes.

The best shape for the moving coil may be shown to be a single-layer solenoid by the following argument. As $\mathbf{T} = I_2 N_2 \Phi$, with a given fixed coil (i.e. $\Phi$ fixed) the torque depends only on $I_2 N_2$. Now $N_2$ turns of the same diameter carrying $I_2$ amperes will clearly give approximately the same torque in the same field whether they are in a coil of square section or as a solenoid. It is therefore advantageous to arrange the $N_2$ turns in the form which has the least self-inductance. This is the single-layer solenoid. The moving coils must therefore be single-layer solenoids.

### *Sizes of Coils.*

(*a*) *Moving coils.*—Owing to the difficulty of expressing the inductance of coils in a single simple mathematical expression, it is almost impossible to derive a mathematical expression including all the factors which affect the torque in a compensated dynamometer. It is still more difficult to differentiate this with respect to a single variable and so find the value of the radius ($r$) of the coils for which $d\mathbf{T}/dr = 0$. That there is an optimum diameter for the moving coils cannot be doubted, but whether this optimum size is practicable is uncertain.

In view of the complexity of the factors involved, it appeared that the most direct way of obtaining this optimum size was to calculate a series of designs, all having practicable dimensions, in sufficient detail to observe the effect of the changes made upon the range and sensitivity.

(*b*) *Fixed coils.*—The diameter of a moving coil having been decided, the fixed coil must be made as small as possible, yet allowing sufficient clearance for the rotation of the moving coil. For a compensated dynamometer we have also the following theorem.

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* *Bureau of Standards Journal of Research*, 1932, vol. 8, p. 239.

† W. H. NOTTAGE: "The Calculation and Measurement of Inductance and Capacity," 2nd ed., 1925.

* C. V. DRYSDALE and A. C. JOLLEY: "Electrical Measuring Instruments," part I, p. 354.

*To show that for a compensated dynamometer the inductances of the fixed and moving coils should be equal.*—For a fixed value of $I$, and $N_1$ turns on the fixed and compensating coils, the field density ($B$) increases as $N_1$ (approx.). Thus

$$B \doteqdot K_2N_1$$

where $K_2$ is some constant. For a compensated dynamometer the inductance of the compensating winding is equal to $L_f$, the inductance of the fixed coil. Now $L_f$ increases as $N_1^2$ for a fixed coil of fixed diameter and cross-sectional area. Thus

$$L_f = K_1N_1^2$$

where $K_1$ is some constant; $I_2$ varies as $E/(L_f + L_m)$, where $I_2$ and $E$ are respectively the current in and the voltage across the voltage circuit; and $L_m$ is the inductance of the latter. Hence

$$\begin{aligned} \mathbf{T} &= \Phi_2N_2I_2 \\ &= BAN_2I_2 \\ &= K_3BI_2 \end{aligned}$$

Now $\Phi_2$ is the flux through an area $A$ equal to the area of the moving coil, and we regard $N_2$ (the turns on the moving coil) and $L_m$ (the inductance of the moving coil) as fixed. Therefore

$$\begin{aligned} \mathbf{T} &= \frac{K_3K_2N_1E}{L_f + L_m} \\ &= \frac{K_4N_1}{K_1N_1^2 + L_m} \end{aligned}$$

where $K_3$ and $K_4$ are constants.

For maximum torque, $d\mathbf{T}/dN_1 = 0$, whence $L_m = K_1N_1^2$, or $L_m = L_f$.

Thus we should adjust the numbers of turns on the fixed coils so as to make these two inductances equal.

TABLE 1.

*Comparison of Six Designs.*

| | Design 1 | Design 2 | Design 3 | Design 4 | Design 5 | Design 6 |
|---|---|---|---|---|---|---|
| Diam. of moving coil, cm .. .. | 7 | 7 | 5 | 3 | 3 | 3 |
| Turns on moving coil .. .. | 25 | 10 | 25 | 25 | 38 | 25 |
| Inductance of moving coil, μH .. | 97 | 19·5 | 62 | 31·5 | 62·5 | 31·5 |
| Resistance of moving coil, ohms .. | 5·1 | 2·03 | 3·7 | 2·2 | 3·35 | 2·2 |
| Total weight of moving system, g.. | 6 | 4·2 | 4·2 | 3·1 | 3·8 | 3·1 |
| Moment of inertia, g-cm² .. .. | 24 | 13·5 | 9 | 2·03 | 2·8 | 2·03 |
| Stiffness of suspension, dyne-cm/degree .. .. .. | 0·65 | 0·46 | 0·46 | 0·34 | 0·415 | 0·34 |
| Periodic time, sec. .. .. .. | 5 | 4·5 | 3·7 | 2 | 2·15 | 2 |
| Inside diam. of fixed coils, cm .. | 8 | 8 | 6 | 4 | 4 | 4 |
| Turns on fixed coils .. .. | 36 | 36 | 36 | 36 | 36 | 24 |
| Inductance of fixed coils, μH .. | 139 | 139 | 97 | 60·3 | 60·3 | 25·0 |
| Inductance of compensating coils, μH .. .. .. .. | 145 | 145 | 102 | 64·3 | 64·3 | 27·6 |
| Total inductance of voltage circuit, μH .. .. .. .. .. | 242 | 164·5 | 164 | 95·6 | 126·8 | 59·1 |
| Min. resistance of voltage circuit, ohms .. .. .. .. | 76 | 51·5 | 51·5 | 30 | 40 | 18·6 |
| Max. volts .. .. .. .. | 7·6 | 5·15 | 5·15 | 3·0 | 4·0 | 1·86 |
| Max. current (amps.), coils in series | 10 | 10 | 10 | 10 | 10 | 10 |
| Deflection (mm) per mW at 1 metre | 0·42 | 0·37 | 0·51 | 0·5 | 0·48 | 0·52 |
| Deflection (mm) per mW if suspension is adjusted to period of 2 sec. | 0·07 | 0·074 | 0·15 | 0·5 | 0·42 | 0·52 |
| Figure of merit .. .. .. | 0·53 | 0·38 | 0·77 | 1·5 | 1·7 | 0·97 |

*Voltage-Coil Current.*

It is evident that for great sensitivity we should work at as high a value of $I_2$ as possible. In this way, for a given torque we require the minimum turns, and hence the self-inductance is as small as possible. This means that the series resistance can have a lower value and greater sensitivity will be obtained.

In the author's model instrument the shunt current was pushed up to 0·1 amp. As this is about three times the current used in commercial indicating instruments it is considered to be as high as is desirable, but since the instrument is compensated such a current will result in no serious trouble.

With the foregoing theoretical guidance the author worked out several designs. The main results of six of these are given in Table 1.

*Selection of Best Design.*

In comparing designs it is well to note that in all cases a series resistance of 314 ohms per mH has been provided and that the maximum shunt current is 0·1 amp. The deflections per mW can only be compared for instruments having equal periods of oscillation. The results have therefore all been brought to this basis (see bottom of Table 1).

The figure of merit must also include the range. All the current ranges are the same. Clearly, an instrument which will give a deflection of 1 mm per mW and can take a maximum voltage of 10 volts is 10 times as good as one with the same sensitivity but a maximum voltage of 1 volt.

The figure of merit then, for instruments with the same current ranges, may be given as

$$\left(\begin{array}{c}\text{Deflection per mW for}\\ \text{periodic time of 2 sec.}\end{array}\right) \times \left(\begin{array}{c}\text{Maximum volts allow-}\\ \text{able on lowest range}\end{array}\right)$$

With this figure of merit as the criterion it is quite clear that No. 5 is the best design, and this one also fulfils the theoretical expectations.

It is noted that when $L_f$ is made equal to $L_m$ the best results are obtained. Table 1 shows clearly that nothing is to be gained by increase in size. It shows also that decrease in $N_1$ or $N_2$ is disadvantageous. It is clear that increase in $N_1$ or $N_2$ or both above the values taken will result in a reduction in sensitivity on account of the increased inductance and increase in control necessary to keep the period of oscillation down to 2 sec. The sensitivity in the case of Design 5 is all that is required; though increasing the turns might improve the figure of merit on account of the increased range, the reduction in sensitivity is not desirable nor is further increased range likely to prove a great advantage, since this can always be obtained by added series resistance. The table does not show that further decrease in size would not be an improvement, but, since the weight of the spindle is, at this size, becoming an important part of the total weight of the moving system, it is unlikely that any great improvement would result. In any case, if the coils are made much smaller than those for Design 5, considerable practical difficulty is likely to result. It is felt that the dimensions arrived at in Design 5 are very close to, if not actually, the optimum values.

The period of oscillation in this case (2·15 sec.) is good. With a deflection of 0·5 mm per mW no difficulty should be experienced in balancing the dynamometers to 0·5 mW.

As the coils are small the instrument should be fairly cheap and compact. So low a figure as 127 $\mu$H for the total shunt inductance of a compensated wattmeter has not, to the author's knowledge, been approached previously in wattmeter design.

The dimensions having been decided upon, the selected design will now be worked out as an illustration of the method of calculation.

### SKETCH OF METHOD OF DESIGN.

*Moving System.*

Shunt current 0·1 amp.; coils, 38 turns of No. 38 S.W.G. double silk covered wire, diameter 3 cm, wound as single-layer solenoids; calculated inductance of coils 62·0 $\mu$H, resistance 3·35 ohms, weight of wire 0·58 g; former,* tufnol ring 0·06 cm thick, 0·85 cm wide, weight 0·66 g; spindle, of tufnol, 14 cm long, 10 cm at 3 mm diameter and 4 cm at 2 mm diameter, weight 1·2 g; total weight of moving system 3·8 g; moment of inertia 2·8 g-cm$^2$; suspension,† bifilar, 10 cm long, distance apart of ligaments 0·5 cm, torsion 0·415 dyne-cm per degree, periodic time 2·15 sec.

*Fixed Coils.*

Number of turns 36; inside diameter 4 cm, leaving 0·5 cm clearance all round moving coil; wound in two halves placed 0·5 cm apart, each half consisting of 18 turns—6 layers, 3 turns per layer (thus approaching square cross-section); the halves can be connected in series or parallel for 10 or 20 amps. respectively.

*General.*

The fixed (or current) coils are wound side by side with compensating windings having the same number of turns (36). The compensating windings are connected in the voltage circuit; their halves must be in series when the halves of the current coils are in series and in parallel when the current coils are paralleled. Hence each terminal board will carry two series/parallel arrangements, one for current coils and the other for compensating coils.

The compensating windings may be constructed of thicker wire than No. 38 S.W.G.; if this is done the copper resistance of the voltage circuit will be reduced, and the coils will be much easier to wind.

The fixed coils are wound with 162/·0076-in. wire designed to carry 10 amps., the calculated inductance of each half being 19·9 $\mu$H, and the calculated mutual inductance between halves 10·25 $\mu$H. The correction for spacing in the case of the compensating coils is 2·0 $\mu$H, and the inductance of the compensating winding with the halves in series is $2(2 + 19\cdot9 + 10\cdot25)$ $\mu$H $= 64\cdot3$ $\mu$H. The inductance of the current winding with the halves in series is 60·3 $\mu$H. The inductance of the voltage circuit with series compensation is $64\cdot3 + 62\cdot5$ $(= 126\cdot8)$ $\mu$H.

The resistance of the compensating winding (No. 28 S.W.G.) is 1·13 ohms, and the total copper resistance of the voltage circuit without added series resistance is 4·48 ohms.

For a wattmeter to give indications within 0·001 in the power factor at any power factor, we need 314 ohms per mH of inductance in the voltage circuit. The total resistance of the voltage circuit on the lowest voltage range must be at least $314 \times 0{\cdot}1268$ (= 40·0) ohms. The added resistance must therefore be $40 - 4{\cdot}5$ (= 35·5) ohms. Thus (Added resistance)/(Copper resistance) = 8. The temperature error will therefore not exceed 0·1 per cent if a difference in temperature between the two moving coils greater than 2 deg. C. does not occur.

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* In practice it was found better to wind the coil in two halves, one on each side of the spindle. This necessitated a wider former, but the weight was reduced to a value less than this calculated value by making it thinner and milling holes in the central blank portion. This course also further reduced the inductance.

† In the actual instrument the top bifilar suspension was used to lead the current to the top moving coil, and another pair of suspensions was added at the bottom to lead the current to the bottom moving coil. The jockey-pulley arrangement shown in Fig. 5 was used. In order to keep the period of oscillation at the required value the top suspensions were put closer together, so that the combined effect of both top and bottom suspensions gave approximately the same torque as that calculated above.

For the moving coils the $I^2R$ loss is 0·034 watt, and the area available to dissipate heat is 14 cm$^2$; thus the dissipation per unit area is 0·0025 watt per cm$^2$. Taking the emissivity as 0·002 watt per cm$^2$ per deg. C., we see that the temperature-rise of the moving coils at full voltage will not exceed 1·25 deg. C. Temperature errors should therefore be well within 0·1 per cent.

Maximum voltage on the lowest range is 4·0 volts. Voltage ranges for maximum voltages of 4·0, 10·0, 40, 150, and 300 volts, are provided by adding series resistances of 35·5, 95·5, 395·5, 1 495·5, and 2 995·5 ohms. A wire woven resistance net tapped at the required intervals is used for this purpose.

### *Sensitivity.*

The flux per ampere obtainable from the current coils with series connection is determined from the value of the inductance, namely 168 lines per amp. Assuming that these lines all pass through a circle 5 cm in diameter, we get for the flux density within the current coils an average value of 8·5 lines per cm$^2$ per amp. Assuming an applied power of 1 mW, $I_2 = 0{\cdot}001$ amp., $E = 0{\cdot}04$ volt, and that the main current is 0·025 amp., we find

$$B = 0{\cdot}025 \times 8{\cdot}5\,(= 0{\cdot}212) \text{ lines per cm}^2,$$

and

$$\mathbf{T} = 0{\cdot}212\pi \times (1{\cdot}5)^2 \times 0{\cdot}001 \times 3{\cdot}8\,(= 0{\cdot}0057) \text{ dyne-cm}$$

Here the estimation is slightly optimistic, since we are assuming that the average value of $B$ for the current coils will be the same as the average value within a 3-cm diameter circle inside the current coils, while in fact the average value here will be slightly less. The deflection will be $0{\cdot}0057/0{\cdot}415\,(= 0{\cdot}0138^\circ)$. This means a deflection of 0·48 mm (say, 0·5 mm) at 1 m.

Estimating that this result is 20 per cent high on account of the fact just mentioned, it is safe to assume that an instrument carried out according to this design would give a deflection of 0·4 mm per mW. No difficulty should be experienced in working to 0·5 mW with moderately careful use of the instrument.

Assuming no error in the d.c. measurement of the voltage and current, it is clear that if on the 4-volt 10-amp. range it is possible to detect a change of 0·5 mW then the sensitivity on the other ranges will be as follows:—

*Current coils in series, maximum current* 10 *amps.**—On the 4-volt range 0·5 mW, on the 10-volt range 1·2 mW, on the 40-volt range 5 mW, on the 150-volt range 19 mW, and on the 300-volt range 37 mW.

*Current coils in parallel, maximum current* 20 *amps.*†—On the 4-volt range 1 mW, on the 10-volt range 2·5 mW, on the 40-volt range 10 mW, on the 150-volt range 37 mW, and on the 300-volt range 75 mW.

It will be noticed that the accuracy of balance obtainable on all ranges, with the full volt-amperes at unity power factor, and assuming that the resistances of the two voltage circuits are the same to such an accuracy, is 1 in 80 000. Clearly then, under all conditions of working above $\frac{1}{80}$ full volt-amperes, the balancing of the instrument will not involve an error greater than 0·1 per cent.

### *Coils for Neutralizing the Earth's Field.*

A coil of 40 turns of No. 32 S.W.G. wound over the current coils and having a resistance of 2·9 ohms will produce a flux density at its centre of 0·2 line per cm$^2$ when a current of 16 milliamps. is flowing in it. Such coils were wound on the instrument and supplied from a 2-volt accumulator through high-resistance potential dividers.

### *Practical Details.*

Using the foregoing technical data, a practical instrument was designed and drawn out as shown in Figs. 5 and 6. Fig. 7 is a theoretical diagram of connections of one dynamometer. The connections of the two dynamometers were identical. Figs. 8 and 9 show the completed instrument.

*Compensating arrangements.*—The added series resistances in the voltage circuit were arranged to be correct with the compensating coils in series. The measured resistance of the compensating coils in series is 1·266 ohms, and in parallel is 0·316 ohm. Thus when the compensating coils are in parallel the resistance of the voltage circuit is reduced by 0·95 ohm. Since the d.c. instrument will always be used without compensation and the a.c. instrument may be used with either series or parallel compensation or without compensation, it is essential that the resistances of the voltage systems be maintained at the correct values if multiplying factors are to be used. In the author's instrument this difficulty was overcome by providing two extra resistance boxes which make possible the addition of 1·266 ohms for "no compensation" and 0·95 ohm for "parallel compensation" to the voltage circuit of either or both instruments. In a professionally constructed instrument this could easily be arranged by fitting an extra plug on each plug-board.

If no compensation is used, the series/parallel plugs short-circuit the ends of the compensating windings. On the a.c. dynamometer this would certainly cause an error due to induction. On the d.c. instrument (where no compensation will be used), since the compensating windings are of low resistance, it was found that even with the three plugs in position a small proportion of the shunt current still flowed in the compensating coils, giving rise to an error. To overcome these troubles the links marked "Compensating circuits" were introduced in the connections to the compensating coils; so that, if no compensation is used, these circuits may be opened. Hence if compensation is used, the plugs must be inserted either in holes 1 and 1a or in holes 2, 2a, 3, and 3a. The links should be removed if the plugs are left in holes 1a, 2a, and 3a. All connections to the coils

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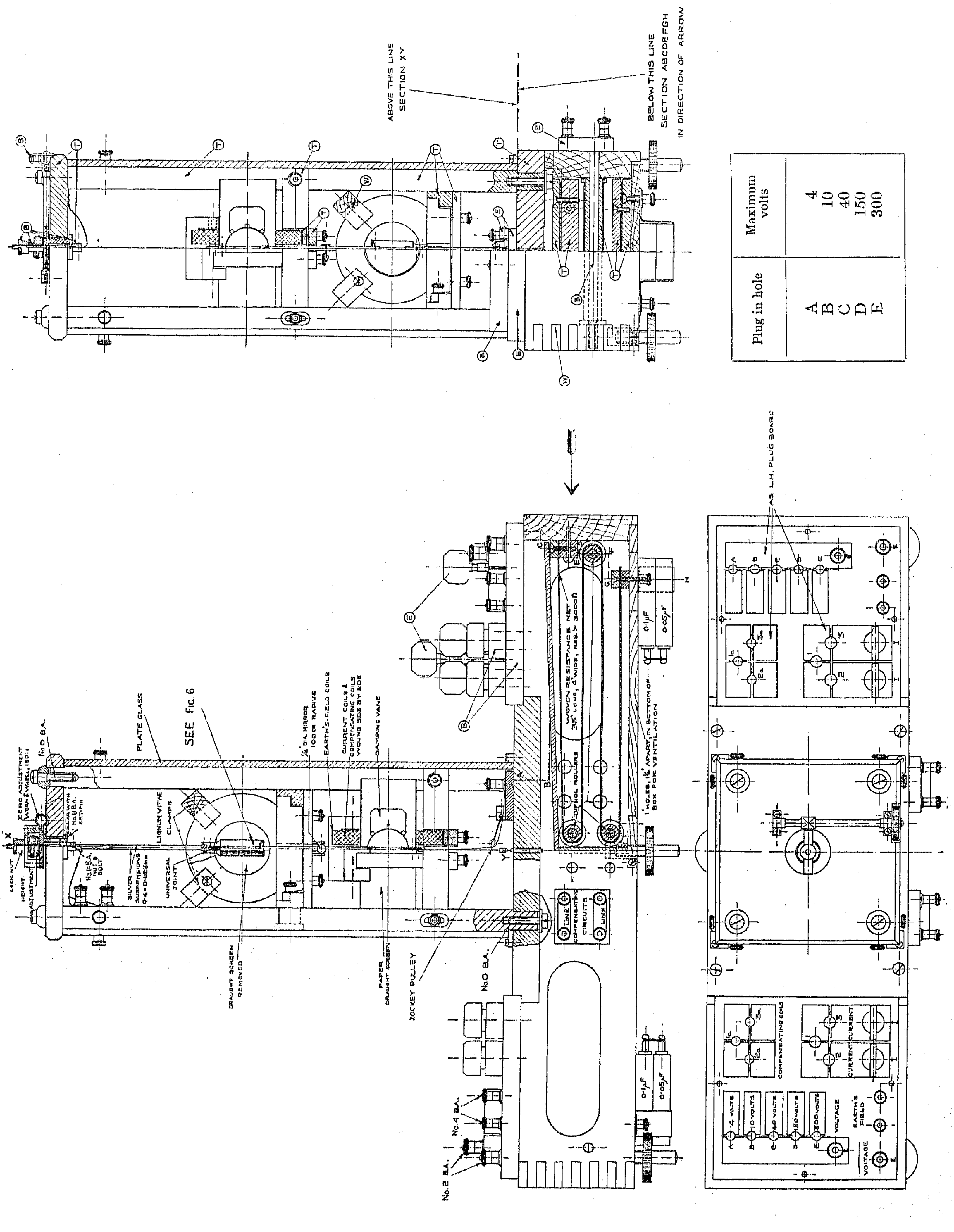
* Plugs in holes marked 1 (Fig. 5).

† Plugs in holes marked 2 and 3 (Fig. 5).



| Plug in hole | Maximum volts |
|---|---|
| A | 4 |
| B | 10 |
| C | 40 |
| D | 150 |
| E | 300 |

FIG. 5.—General arrangement of iron-loss wattmeter. Scale: $\frac{1}{17}$ full size.

Materials { Brass (B) Tufnol (T) Wood (W) Ebonite (E) are brought down to plug boards in pairs through appropriate holes in the tufnol base.

*Suspension and leading-in ligaments.*—Tests were carried out on a number of phosphor-bronze and silver strips with a view to finding their change of resistance when carrying the required currents. A silver strip was finally selected for use, this being many times better—from the point of view considered—than phosphor-bronze strips of the same size. The cross-section of the strip taken was 0·4 mm by 0·023 mm. The total change in resistance of 24 cm of this (the length in circuit) when the current changed from 0·02 to 0·1 amp., reckoned as a percentage of the total resistance of 40 ohms, was only 0·002 per cent.

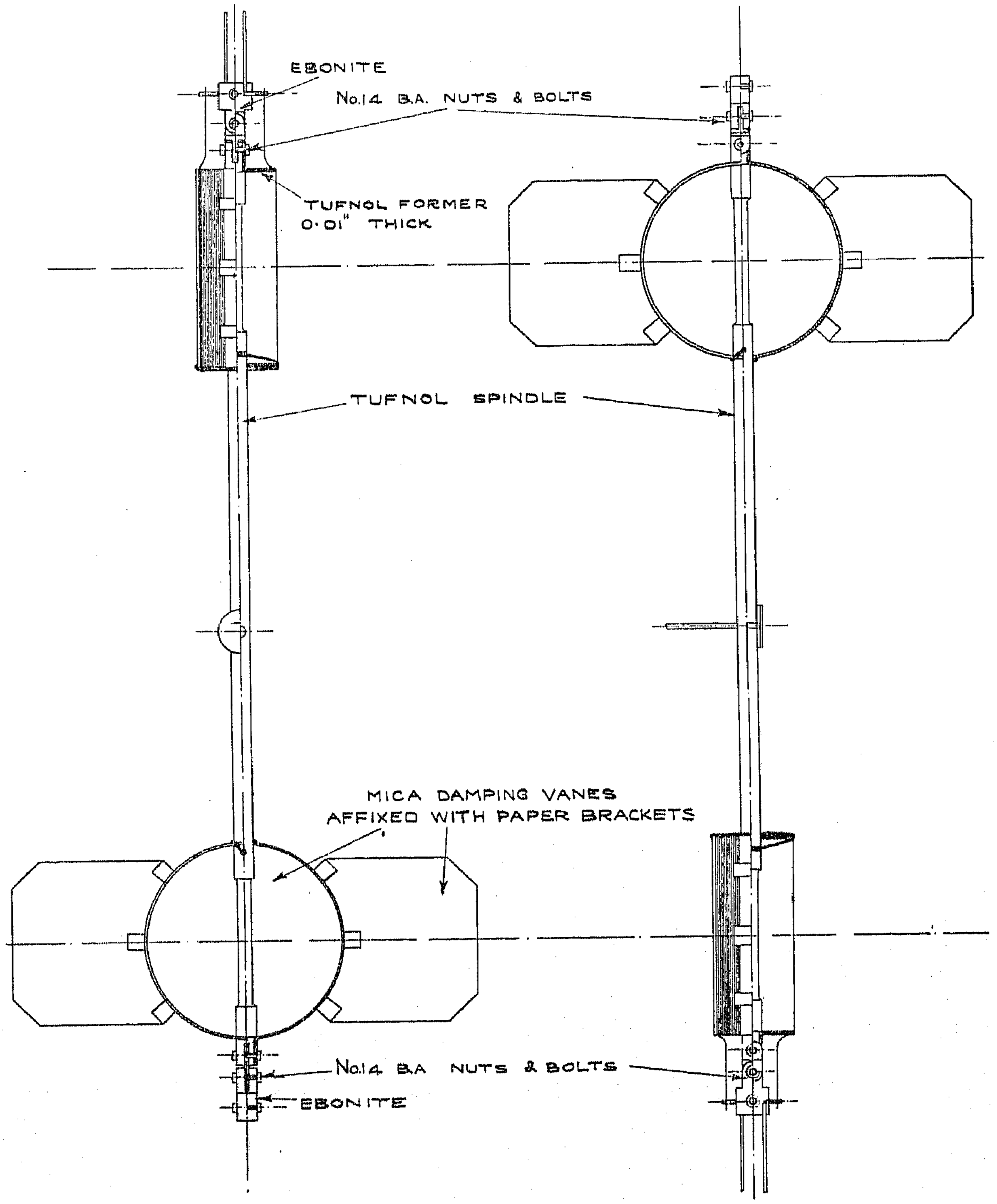


FIG. 6.—The moving system. (Approx. $\frac{3}{5}$ full size.)

### TESTS ON THE COMPLETED INSTRUMENT.

*Period of Oscillation.*

With the above silver strip used for both top and bottom suspensions, the period of oscillation was found to be 2·4 sec. This was accepted as satisfactory, seeing that little increase in ease of manipulation is to be gained by stiffening the suspension so as to give a period of oscillation of 2 sec. The longer period of oscillation also tends to cancel the decrease in sensitivity due to having the fixed coils 0·7 cm apart (this was found necessary on completion) instead of 0·5 cm as in the theoretical design.

*Measurements of Resistances and Inductances.*

The experimental values of the resistances (measured on the Feussner bridge) and inductances (determined by reference to a variable standard self- and mutual inductance at 1 000 cycles per sec.) were found to be in good agreement with the calculated design values. The final values of the resistances, showing the accuracy with which the two instruments were balanced in this respect, are given in Table 2.

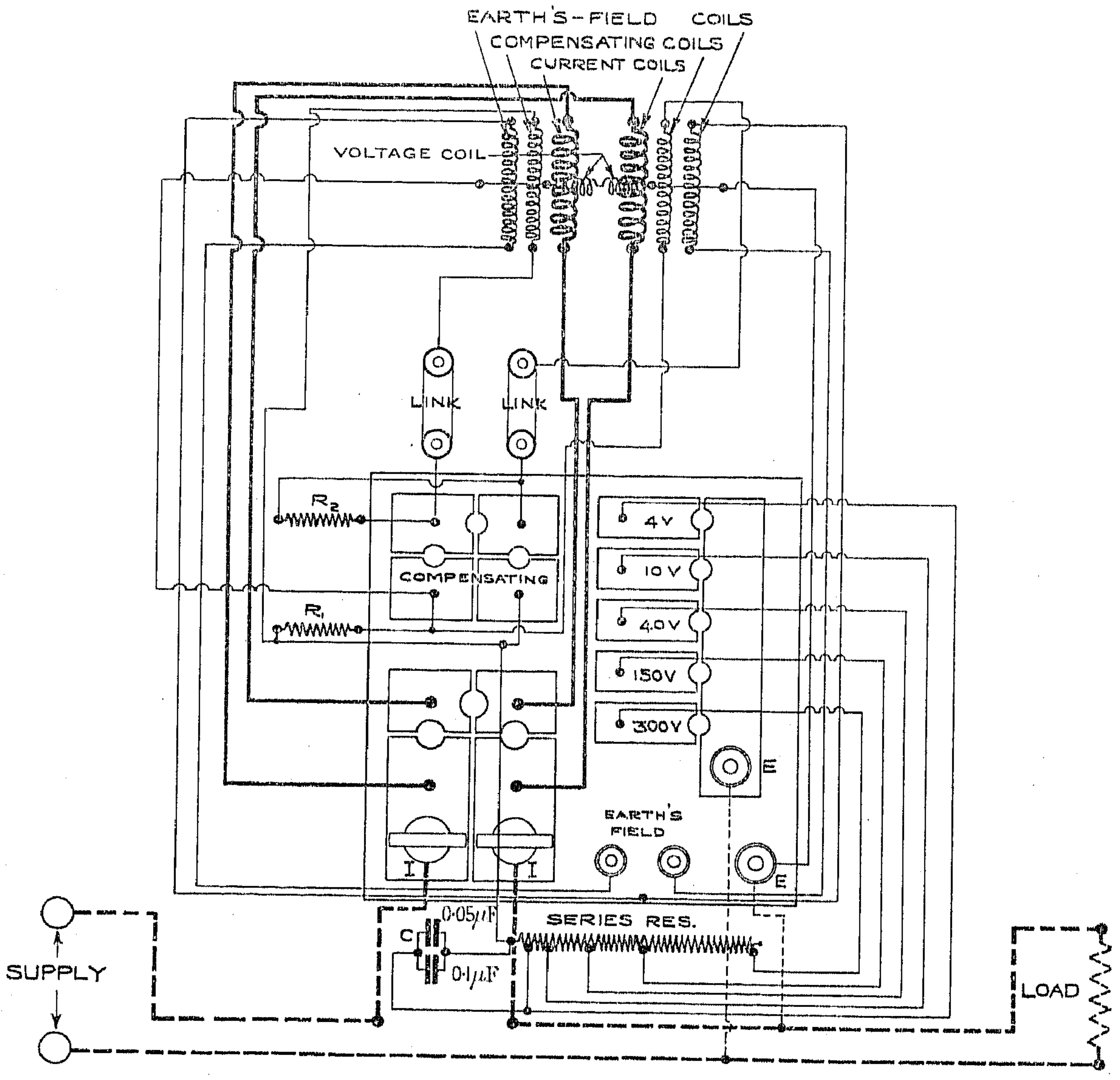


FIG. 7.—Iron-loss wattmeter: diagram of connections.

$R_1$ and $R_2$ correct the compensation.
C corrects the inductance error.

Internal connections ——
External connections — — —

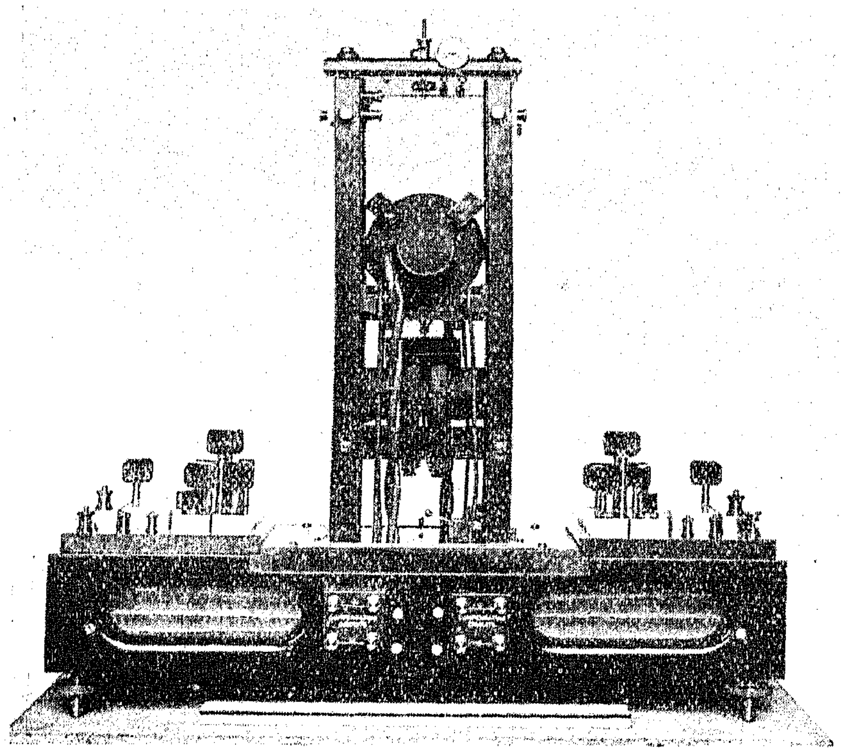


FIG. 8.

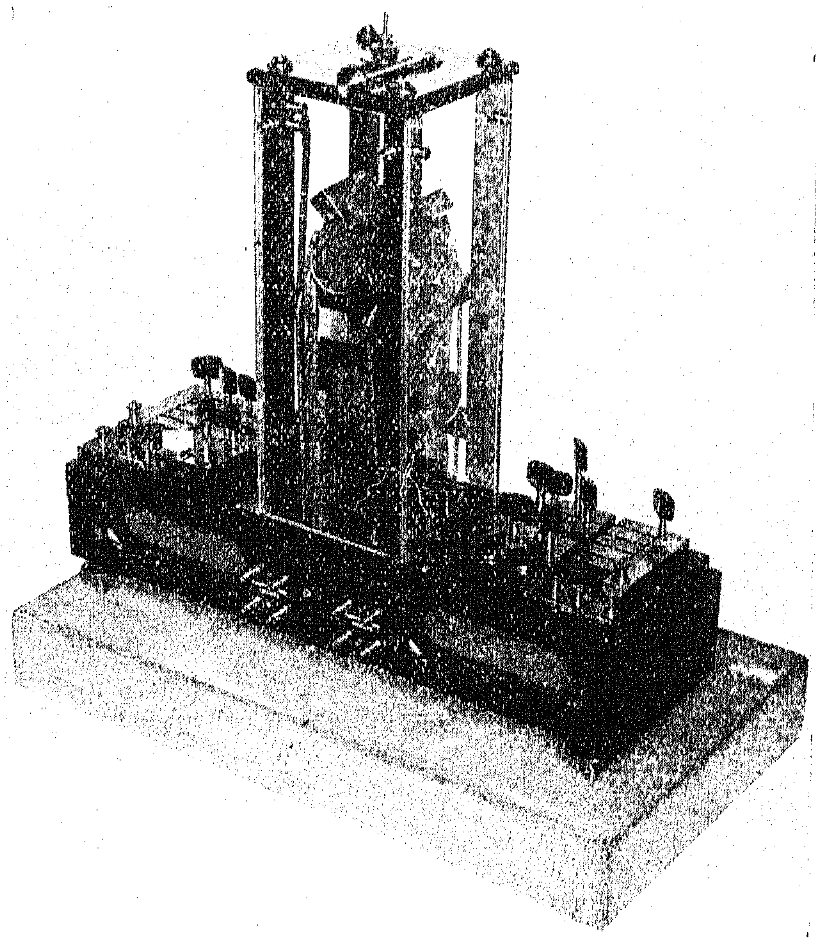


FIG. 9.

### *Balancing the Earth's Field.*

The earth's-field coils were connected to a 2-volt accumulator as shown in Fig. 10. With no compensation and a potential difference of 4 volts across the 4-volt range of the voltage circuit of the left-hand instrument, the deflection due to the earth's field was reduced to zero by adjusting the current in the earth's-field coil. This operation was repeated for the right-hand instrument.

With the particular orientation of the instrument in use the currents required for this compensation were: left-hand instrument, 4·8 milliamps.; right-hand instrument, 38 milliamps.

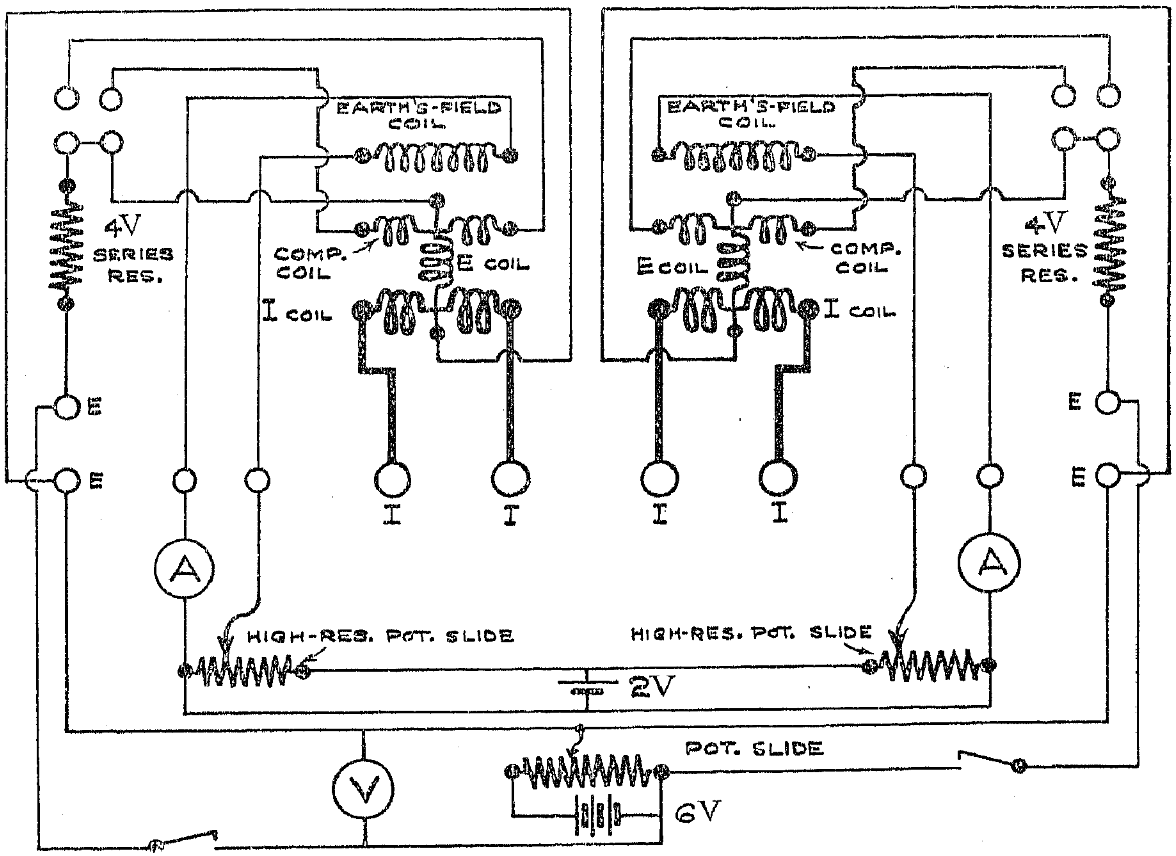


FIG. 10.—Diagram of connections for balancing out the earth's field.

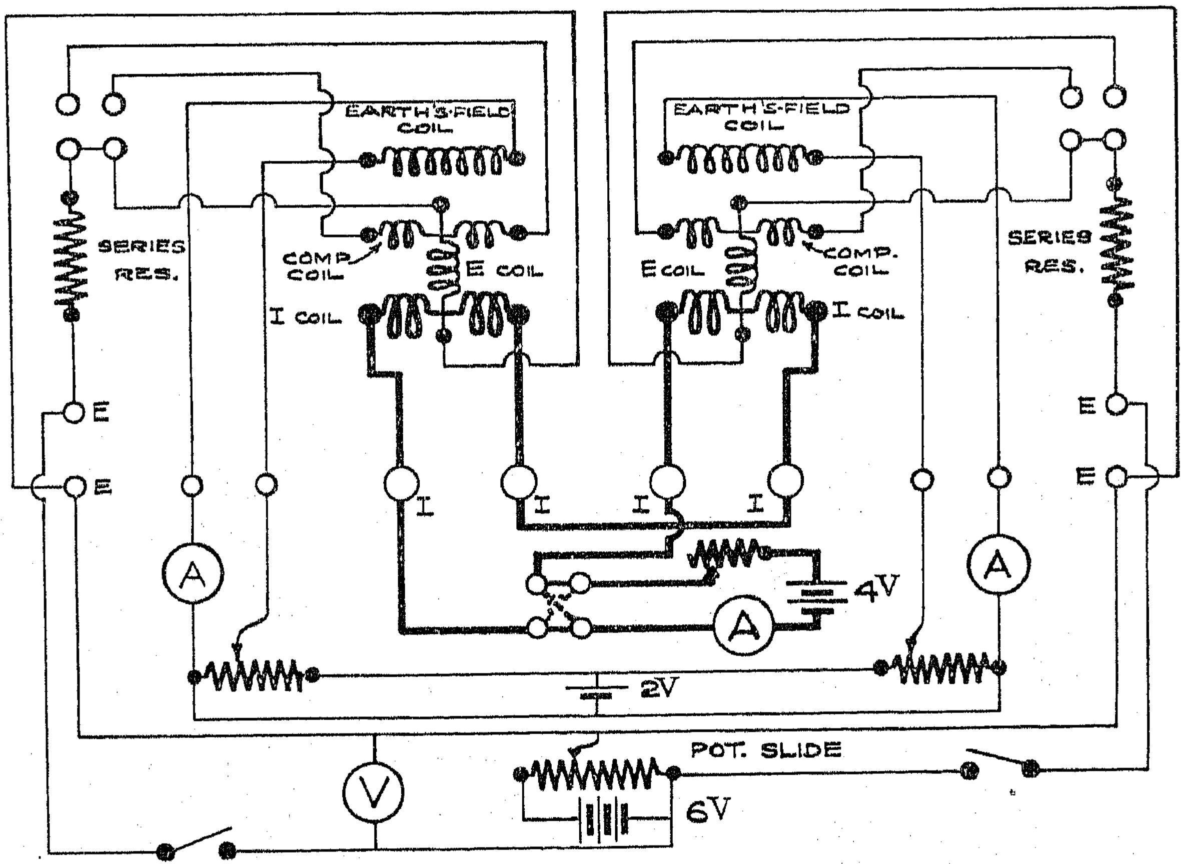


FIG. 11.—Diagram of connections for sensitivity and d.c. balancing tests.

### *Test of Sensitivity.*

The scale was set up at a distance of 1 m and the instrument levelled and adjusted to zero. The voltage circuits were arranged for no compensation. The instrument was connected as shown in Fig. 11. The deflection of each instrument was noted when a current of 0·1 amp. was passed through the current coil and a potential difference of 1 volt was applied to the voltage circuit.

The deflections for 100 mW were the same for both instruments, namely 62·5 divisions (1 division = 0·025 in. Thus the sensitivity is 625 divisions per watt, or 0·39 mm per mW. This should be compared with the design figure of 0·4 mm per mW.

### *Effect of Current in the Fixed Coils Only.*

As has already been mentioned in the discussion of possible errors, it was found that the convection currents rising from the fixed coils and impinging on the mica damping vanes attached to the moving coils caused considerable deflections. To overcome this, the draught shields shown in Fig. 5 were fitted. With these shields the effect of a current of 10 amps. in the fixed coils only was as follows: in the top coils only, a deflection to the left gradually increasing to 0·5 division after 10 minutes; in the bottom coils only, a deflection to the right gradually increasing to 2·5 divisions after 10 minutes; in both top and bottom coils, a deflection to the right gradually increasing to 3 divisions after 10 minutes.

It appears that the change of zero due to the heating of the fixed coils is largely caused by the heating of the lower coils, as would be expected. The change due to the top coil alone is negligible. Hence it is advisable to use the upper dynamometer as the a.c. instrument, since at low power factors the current in the lower coil can be much lower than the full value, and the error introduced will be very small. The error will be shown to be quite negligible in the case where the instrument is used on a.c./d.c. supplies. The only time when the error may be troublesome is during checking of the instrument with the full volt-amperes in each system. Since the change is slow it is quite easy to adjust the zero during this checking test, if this is considered necessary.

### *Percentage Error due to Heating of Current Coils if Zero is Left Unadjusted.*

With 10 amps., 4 volts, alternating current at unity power factor: $I$ (d.c.) = 10 amps., error = 3 divisions, or 3/625 watt in 40 watts, or 0·012 per cent.

With 10 amps., 4 volts, alternating current at 0·1 power factor, $I$ (d.c.) = 1 amp., deflection due to 10 amps. in top coils is 0·5 division, deflection due to 1 amp. in bottom coils is 0·03 division; thus error is, say, 0·5 division, or 1/1 250 watt in 4 watts, or 0·02 per cent.

It is therefore clear that, since the above conditions of working at the full volt-amperes are the worst, the error from this cause will never exceed, say, 0·05 per cent.

### *Balancing the Torques of the Two Dynamometers.*

The instrument was connected as shown in Fig. 11. Any torque between one fixed system and the other moving system, with direct current in both, must first be eliminated. The procedure is as follows:—

(1) Balance out the earth's field on both dynamometers.

(2) With the full current in the top current coils and full voltage across the bottom voltage circuit, adjust the zero so that no deflection is produced when the current is reversed.

(3) With the full current in the bottom current coils and full voltage across the top voltage circuit, adjust the angle of the bottom current coils on the cross slides so that no deflection is produced when the current is reversed. We now have the instrument and its zero adjusted so that no torque is produced on one system by the other with direct current in each. This zero should be maintained as the true zero. (It was found possible to make this adjustment to within 0·5 division.)

(4) With the full voltage on and current in both instruments, and with the latter connected so that their torques oppose, adjust the distance apart of one pair of fixed coils so that the best possible balance is obtained on the 4-volt and 10-volt ranges.

Under these conditions, with the current coils in series, the balancing error on the 4-volt and 10-volt ranges did not exceed 1 in 4 000, and on no range did the error exceed 1 in 1 500. These errors will not be exceeded whatever volt-ampere values are measured. In a professionally constructed instrument much greater accuracy of balance than this would be obtained, but since the accuracy exceeded the limit aimed at it was considered by the author to be quite satisfactory.

### *Effectiveness of Compensation.*

This was checked by passing a current of 0·1 amp. through the voltage and current circuits connected in series and with the voltage circuit arranged for compensation. It was checked on both instruments and found to be over-compensating. The actual deflections were:—

Left-hand instrument: series compensation 13 divisions left, parallel compensation 7 divisions left.

Right-hand instrument: series compensation 9 divisions right, parallel compensation 4·5 divisions right.

It is essential that the compensation should be exact since, when the instrument is being used at low power factors with the full voltage, these errors, which depend on the voltage only, will become very large in proportion to the watts measured.

Since the coils over-compensate, their effect can be reduced by shunting with fairly high resistances. These are the resistances $R_1$ and $R_2$ shown in Fig. 7. Their values were obtained on test at 50 cycles per sec. and were found to be:—

For left-hand instrument: $R_1 = 26\cdot5$ ohms,
$R_2 = 8\cdot5$ ohms.
For right-hand instrument: $R_1 = 34\cdot9$ ohms,
$R_2 = 10\cdot3$ ohms.

These resistances, connected as shown, made the compensation so good that no deflection greater than 0·25 division could be observed when a 4-volt 50-cycle supply was applied to the current and voltage circuits in series. The insertion of these resistances altered the total resistances of the voltage circuits by a very small amount. The final values of the resistances on the various ranges are given in Tables 2 and 3.

The resistances of the extra boxes* were made up as follows:—

For left-hand instrument: parallel compensation 0·96 ohm, no compensation 1·28 ohms.
For right-hand instrument: parallel compensation 0·94 ohm, no compensation 1·26 ohms.

These resistances are such as to make the resistances of the voltage circuits on the 4-volt ranges each equal to 40·04 ohms, which is the mean of the two resistances with series compensation. Hence with one instrument with no compensation and the other with series compensation the resistances are balanced to 1 in 4 000, or 0·025 per cent.

TABLE 2.

*Final Resistances of Voltage Circuits with Series Compensation.*

| Range | Left-hand instrument | Right-hand instrument | Percentage difference |
|---|---|---|---|
| volts | ohms | ohms | |
| 4 | 40·03 | 40·05 | 0·05 |
| 10 | 99·98 | 100·00 | 0·02 |
| 40 | 399·92 | 399·89 | 0·01 |
| 150 | 1 499·61 | 1 499·46 | 0·01 |
| 300 | 2 998·91 | 2 998·70 | 0·01 |

*Zero Power Factor Test.*

If such a wattmeter is satisfactory as regards power-factor error at zero power factor, the error at zero power factor will not be exceeded at any other power factor. It is therefore desirable to apply the full volt-amperes to the instrument at zero power factor, note the deflection, and if necessary adjust it by means of a suitable condenser.

The method of obtaining zero power factor is shown in Fig. 12. It makes use of inductance, resistance, and capacitance. The condition for zero power factor can easily be shown to be

$$\frac{L}{C} = R_p R_i$$

where $L$ and $R_i$ are the inductance and resistance of the current circuit, and $C$ and $R_p$ are the capacitance and resistance in the voltage circuit. This expression shows that zero power factor is obtained independent of the frequency. The method will therefore be effective whether the wave-form of the supply is a pure sine wave or not.

TABLE 3.

*Final Resistances of Voltage Circuits on 4-volt Ranges.*

| Without extra box | Left-hand instrument | Right-hand instrument | Percentage difference |
|---|---|---|---|
| | ohms | ohms | |
| Parallel compensation | 39·08 | 39·10 | 0·05 |
| No compensation .. | 38·76 | 38·78 | 0·05 |

In the actual tests the values of $L$, $R$, and $C$, were not relied on, but a vibration galvanometer and mutual inductance were used as shown. The voltage induced in $L_2$ is in quadrature with $I$, being exactly equal to $-j\omega MI$. If, therefore, by adjusting $I_p$ by means of C and R and arranging for the value of $M$ to be variable we can obtain a balance on the vibration galvanometer, we then know that the voltage across AB is in exact quadrature with the current $I$. The method was found to be very satisfactory provided care was taken to avoid inductive loops in the wiring-up of the apparatus.

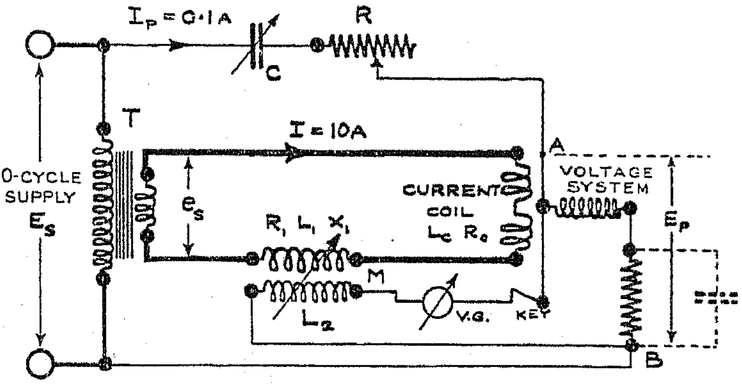


FIG. 12.—Diagram of connections used for zero-power-factor tests.

Clearly, these tests can only be carried out without compensation, since the use of compensation would cause a large permanent deflection as a dynamometer voltmeter. The left-hand and right-hand instruments were found to have identical performances on zero power factor. The results given apply, therefore, to both instruments.

TABLE 4.

*Errors at Zero Power Factor with No Compensation. Full Volt-amperes, and Current Coils in series.*

| | | On 4-volt range | On 10-volt range |
|---|---|---|---|
| Deflections (in divisions) | $C_E = 0$ | 24 | 14 |
| | $C_E = 0\cdot1$ | 0 | 6 |
| | $C_E = 0\cdot15$ | 12 | 1 |
| Watts indicated | $C_E = 0$ | 0·038 | 0·056 |
| | $C_E = 0\cdot1$ | 0·000 | 0·024 |
| | $C_E = 0\cdot15$ | 0·019 | 0·004 |
| Volt-amperes .. | .. .. | 40 | 100 |
| Errors in power factor | $C_E = 0$ | $0\cdot0009_5 i$ | $0\cdot0005_6 i$ |
| | $C_E = 0\cdot1$ | 0·0000 | $0\cdot0002_4 i$ |
| | $C_E = 0\cdot15$ | $0\cdot0004_7 c$ | $0\cdot0000_4 i$ |

Tests were carried out on the 4-volt and 10-volt ranges, both without and with the condenser $C_E$ shown dotted in Fig. 12. The values of $C_E$ used were 0·1 and 0·15 μF, these being connected across the resistances on the 4-volt ranges in all cases.

In Tables 4 and 5, $i$ indicates inductive error, and $c$

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* The extra box is referred to on page 213, under "Practical Details".

indicates capacitive error. For the errors with compensation we must add to these errors those due to the addition of the inductance of the compensating coils, i.e. 57 $\mu$H. Thus for series compensation we have to add inductive errors of $0 \cdot 0004_5$ on the 4-volt range and $0 \cdot 0001_8$ on the 10-volt range.

Referring to Table 5, the errors with $C_E = 0 \cdot 15\ \mu$F are so small that it was decided to connect a condenser of $0 \cdot 15\ \mu$F permanently across the series resistance of the 4-volt range of each dynamometer. The errors on the ranges higher than the 10-volt range will be even less than these. It must therefore be admitted that the performance on zero power factor is excellent.

It appears that no eddy currents occur in the current coils, since the inductive errors without the condenser and with series compensation are actually greater than the calculated values. This is presumably due to the slight inductance of the series resistance, which in the design was assumed non-inductive.

TABLE 5.

*Errors at Zero Power Factor with Series Compensation.*

| | | On 4-volt range | On 10-volt range |
|---|---|---|---|
| Errors in power factor | $C_E = 0$ | $0 \cdot 0014i$ | $0 \cdot 0007_4 i$ |
| | $C_E = 0 \cdot 1$ | $0 \cdot 0004_5 i$ | $0 \cdot 0004_2 i$ |
| | $C_E = 0 \cdot 15$ | $0 \cdot 0000_2 c$ | $0 \cdot 0002_2 i$ |
| Error angle with $C_E = 0 \cdot 15\ \mu$F | | Negligible | About 1 minute |

*Use of the Instrument.*

All the necessary tests having been satisfactorily completed, the instrument was arranged for use with suitable supplies and regulating resistances, and a rough test was carried out on an iron-ring sample weighing $0 \cdot 5$ kg in order to test the ease of manipulation. The operation of the instrument was found to be easy and quick, there being little or no waiting for oscillations to die down when obtaining a balance.

*With the Epstein square and* 10 *kg of iron.*—The lowest value of $B$ at which good readings could be taken was about 6 000 lines per cm$^2$. At this value, readings of watts could not be guaranteed to less than 10 per cent. The values obtained, however, gave good agreement with those determined for $B = 6\,000$ using the author's wattmeter.

*With the iron-loss wattmeter and* $0 \cdot 5$ *kg of iron.*—Readings could be obtained with values of $B$ as low as 300 ($\frac{1}{20}$ of the Epstein-square value), and these are of at least as good an order of accuracy as those for $B = 6\,000$ on the Epstein square. With the higher values of $B$ (values which give a loss greater than $0 \cdot 1$ watt) the overall accuracy will be within $0 \cdot 5$ per cent.

Thus for iron-loss testing the iron-loss wattmeter gives an improvement over the Epstein square and indicating wattmeter of 20 times on account of the value of $B$, and a further improvement of 20 times on account of the weight of iron used. In other words, broadly speaking, the iron-loss wattmeter used with a small ring sample is at least 400 times as effective as the Epstein square and an indicating wattmeter, if merit can be treated in this way.

In commercial practice, readings at these low values of $B$ would not be required, the value of 10 000 lines per cm$^2$ being the specified test figure. Since the greatest difficulties were likely to be met in measuring at the lower values, no difficulty is anticipated in measuring at higher values, the range of the instrument being so extensive.

If readings at $B = 10\,000$ only are required, then, clearly, the winding on the sample should be chosen so as to give a value of $E$ equal to about 4 volts (assuming that a current of 20 amps. is not exceeded). Several advantages are associated with such a choice:—

(*a*) The 4-volt range of the wattmeter is the most sensitive, and great precision should be obtained.

(*b*) The current will probably be fairly high and the $I^2R$ correction will be more accurate, since the shunt current will be small compared with the main current.

(*c*) The winding on the sample will then have the minimum number of turns.

(*d*) An even smaller weight of iron than $0 \cdot 5$ kg could easily be used (say 100 g).

If readings over a wide range of values of $B$ are required, in order to keep the voltage and current on the best ranges of the wattmeter it will probably be advantageous—though not essential—to wind such a ring sample as that taken, with four windings in parallel. The ends of these can be connected in series, in series-parallel, or in parallel, giving three or more alternative numbers of turns and current-carrying capacities.

## CONCLUSION.

Though the original object of the investigation was the development of the wattmeter, the work naturally led on to the iron-loss measurements, and it was to show some of the possibilities and difficulties of the use of the instrument in this connection that the last rough test was undertaken. The tests served their purpose very well by indicating (*a*) the great improvement over the Epstein square and indicating wattmeter, (*b*) that the instrument is suitable for iron-loss measurements on quite small weights of iron.

The previous work has proved the instrument to be capable of great precision. The accuracy is determined by two main factors: (i) The accuracy of the d.c. instruments, if these are used to measure the d.c. watts. (ii) The fact that $0 \cdot 0005$ watt is the smallest power detectable. Since (i) can only be guaranteed to $0 \cdot 5$ per cent, it follows that, on the 4-volt 10-amp. range, above $0 \cdot 1$ watt and $0 \cdot 05$ power factor the auccracy of the wattmeter exceeds that of the d.c. instruments. Below $0 \cdot 1$ watt we can read to $0 \cdot 0005$ watt. In this case, above $0 \cdot 05$ power factor other errors are smaller than the error in balancing, since they are within $0 \cdot 1$ per cent of the power measured.

On account of the use of the balancing principle, the range is exceptionally wide and the instrument should therefore find fields of application which extend far beyond that for which it was particularly designed.

The wattmeter is essentially a laboratory instrument and if accurate results are to be obtained it must be used and treated with care. The advantage of great sensitivity has been obtained partly by employing a shunt current which is three times that in normal use in indicating instruments. This fact must be borne in mind and the conditions of use examined to see whether it will introduce any serious error, in which case a correction can easily be applied.

When a satisfactory permeammeter has been devised for *B*/*H* measurements on small samples in strip form, such an apparatus in conjunction with a wattmeter of the type described in this paper should form a very satisfactory and complete iron-testing equipment. When such a permeammeter has been produced to give the precision now readily obtainable in iron-loss measurements by the method described in this paper, the time when iron sheets will be available whose magnetic characteristics are known will not be far distant. The almost prohibitive wastefulness of iron-loss tests on 10-kg samples and *B*/*H* tests on ring samples having thus been abolished, it is hoped that manufacturers will widely install such equipment, which will undoubtedly be a saving to themselves and a benefit to the electrical industry.

## ACKNOWLEDGMENTS.

The author wishes to record his gratitude to Prof. W. Cramp, D.Sc., Member, and to Mr. E. J. Kipps, M.Sc., Member, both of the University of Birmingham, who suggested to him the original idea of the instrument. His thanks are also due to Mr. D. C. Gall, of Messrs. H. Tinsley and Co., who offered several useful criticisms and suggestions during the testing of the instrument.

## APPENDIX.

### ALTERNATIVE METHODS OF MEASURING THE DIRECT CURRENT AND VOLTAGE.

(1) We could reduce the determination of the direct current and voltage to a single measurement. Thus, instead of measuring $E$ and $I$ by two instruments we could, say, measure $I$ only and feed the voltage circuit from a resistance in the current circuit. This appears simple, but unfortunately it introduces a square law, which is a disadvantage. The straight-line scale obtained by using two instruments, fixing $E$ at, say, 1 or 2 or 4 volts, and measuring $I$ when a balance is obtained, is much to be preferred, since the watts are read either directly on the ammeter or by the use of a simple multiplying factor.

(2) We could use a potentiometer to measure $E$ and $I$. This could be applied in three ways: (*a*) Measuring $E$ and $I$ separately after the a.c./d.c. balance had been obtained. (*b*) Reducing the process to a single measurement, as in (1). [In this case, however, the disadvantage mentioned under (1) still holds.] (*c*) Adjusting $E$ to some suitable value compared with a standard cell, keeping it at this value or a simple multiple of it, and measuring $I$ on the potentiometer. Again the value of $I$ gives the watts simply if $E = 1$, 2, or 4 volts.

Reviewing the four methods, (1) is considered inferior to that now in use, since in the first place the scale has a square law and in the second the watts are not given directly from the current. If d.c. indicating instruments are to be used, therefore, the present method is the best.

For commercial work, the d.c. instruments are all that is required. A potentiometer with its galvanometer, mirror, lamp, and scale, would be quite unsuitable. For accurate scientific work, however, it may be felt advantageous to refer directly to the standard cell. With a professionally constructed instrument in which the limits of error were brought much finer, this would probably be justified, and although the accuracy of the potentiometer measurements would even then be in excess of the accuracy of the wattmeter (except perhaps at the higher values of the watts) the total error of measurement would certainly be reduced by this course. If for some purpose it is decided to use a potentiometer, it will probably be found that a mirror galvanometer is unnecessary, more than sufficient accuracy being obtained by a sensitive pointer galvanometer. In this case the use of a potentiometer would not be too troublesome. Also, of the three methods, it is obvious that (*c*) is the best.

For iron-loss measurements it is felt that the use of a potentiometer could not be justified even for scientific work, since it is doubtful whether the frequency of a laboratory supply could be kept constant to within 0·5 per cent, and the d.c. instruments will be at least as accurate as this if they are frequently calibrated.

# NETWORK FAULT RESISTANCE.*

By J. L. Carr, B.Sc., and H. Shackleton, B.Sc., Associate Members.

(*Paper received* 19*th July*, 1934.)

## Summary.

The importance of the systematic determination of the network fault-resistance of a distribution system is referred to, particularly as regards systems employing cables insulated with vulcanized bitumen, or laid solid in bitumen. Supply requirements necessitate such measurement being made without isolating the mains.

For direct-current distribution systems several well-known tests are available: the paper mentions modifications of one method which were successively devised to overcome deficiencies in the original test and to gain more accurate results.

With alternating-current distribution, additional complications arise. A simple method has been developed to enable the fault resistance of a polyphase distribution network to be determined with reasonable accuracy and with a minimum of calculation. A portable testing equipment for this purpose is described.

## Introduction.

In the maintenance of a distribution system it is important that quantitative information should be available regarding leakage from the network. A knowledge of the variation in the amount of leakage is necessary in order to determine the time when the removal of the more serious leaks is essential.

The total leakage is made up of the following components: (1) Surface leakage over cable ends, etc. (2) Leakage through the insulation resistance of feeders and distributors. (3) Incipient faults on the cable system. (4) Leakage on wiring and appliances on consumers' premises. (5) Faults on wiring and consumers' appliances.

From a test on the network it is impossible to determine what proportion of the leakage is due to mains only: the possible damage to other underground works which may be caused by considerable earth currents is, moreover, not limited to leakage from the public supply equipment. With direct-current distribution, the production of electrolytic damage by relatively small return currents must also be considered. Speedy location and disconnection of faulty equipment is therefore desirable.

The Electricity Supply Regulations prescribe the maximum permissible value of leakage, and also require that the voltage of any conductor shall not exceed the limit for low voltage under normal conditions: the system is to be earthed at one point only: on a.c. systems solid earthing is prescribed. Further, the supply is to be maintained without interruption except in special circumstances.

These requirements preclude the measurement of insulation resistance by the usual factory methods.

The importance of adequate network maintenance has been given prominence in recent years because of explosions caused through the ignition of bitumen-vapour mixtures generated by vulcanized bitumen sheathing, and by bitumen filling on solid-laid systems, under the influence of fault conditions. Occurrences of this sort have resulted in the additional requirement of the Electricity Commissioners that such existing lines are to be regularly tested for insulation, and inspected where possible.

The essential requirements for periodical testing of networks are: (i) Tests to be made when the system is "alive." (ii) The earth connection to be interrupted for the minimum period. (iii) The method must lend itself to easy evaluation by mains engineers.

## Direct-Current Systems.

On direct-current systems the problem is relatively simple, since all leakages may be treated as pure resistances. Various methods for testing such networks when alive have been developed by, for example, Frisch, Raphael, Russell, Taylor, and Mullendorff.

The Russell test is simple and yields results satisfactory for the object in view, and with a minimum of calculation, provided that the earth return current is not of very small amount.

A modification of the Russell test, designed with a view to overcoming the defect already mentioned, has been employed on one extensive 3-wire system for many years. The method involves the connection of an artificial leak on one outer conductor, preferably that having the lowest insulation resistance. A suitable ammeter and voltmeter are employed, and are permanently connected with a switch and suitable link arrangements so as to be immediately available. Closing the switch earths the neutral point of the system through the ammeter, after temporary removal of the normal earth connection, the voltmeter being short-circuited by the switch blade. On opening the switch, the voltage of the neutral to earth is observed.

If the fault resistances of the three conductors be $r_1$, $r_2$, and $r_3$, and the fault resistance of the network be $x$, then, by definition,

$$\frac{1}{x} = \frac{1}{r_1} + \frac{1}{r_2} + \frac{1}{r_3}$$

### (*a*) *Russell Test.*

If the reading of the ammeter is $I$ and the reading of the voltmeter is $E$, then $x = E/I$, assuming that the leaks on the positive and negative sides are unequal, the ammeter and earth connection are of negligibly low resistance, and the neutral-conductor fault resistance is relatively high compared with the resistance of the ammeter and earth connection.

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### (*b*) *Modified Test.*

When the value of $I$ approaches zero, a resistance $R$ is connected to one outer conductor, and the test repeated. If the modified value of the fault resistance is now $x'$, the ammeter reading $I'$, and the voltmeter reading $E'$,

Then $$\frac{1}{x'} = \frac{1}{x} + \frac{1}{R}$$

As before, $x' = E'/I'$, so that

$$x = \frac{1}{\dfrac{I'}{E'} - \dfrac{1}{R}}$$

assuming that the neutral-conductor fault resistance is relatively high compared with the resistance of the ammeter and earth connection.

### (*c*) *Improved Test.*

The last method becomes unreliable in the event of a serious leak on the neutral conductor. The following modification has therefore been devised. The two sets of readings are taken as previously described, with the precaution of connecting the artificial leak $R$ to the same side of the network as the predominating fault; that is, the connection of $R$ should increase the instrument readings. In addition, the voltage across this side of the supply is measured: the reading of a busbar voltmeter is usually sufficiently accurate for this purpose. If the voltage of this side is $V$,

Then $$x = \frac{R(E' - E)}{V - E'}$$

This simple formula may be evaluated easily without delay.

The accuracy of the method has been verified in the test room, and the method has subsequently been employed when found necessary. The following examples demonstrate the differences observed, using an artificial leak of 40 ohms.

| Test No. | Test (*a*) | | | Test (*b*) | | | Test (*c*) | |
|---|---|---|---|---|---|---|---|---|
| | $E$ | $I$ | $x$ (calc.) | $E_1$ | $I_1$ | $x$ (calc.) | $V$ | $x$ (calc.) |
| | volts | amps. | ohms | volts | amps. | ohms | volts | ohms |
| 1 | 30 | 0 | ∞ | 195 | 5 | 1 560 | 210 | 440 |
| 2 | 10 | 0·3 | 33 | 9 | 5·4 | 1·7 | 220 | 0·19 |
| 3 | 110 | 2·2 | 50 | 160 | 7·2 | 49·8 | 210 | 40·0 |

## ALTERNATING-CURRENT SYSTEMS.

On an alternating-current system, in addition to pure leakage currents, capacitance currents flow to earth and between conductors in leading quadrature with the appropriate voltage. Dielectric losses are of small amount on medium-voltage systems, and in any case have a similar effect to leakage currents. It is apparent, however, that the methods employed on d.c. networks cannot be applied here.

Leakage indicators may be used on an unearthed system; but as the standard method of supply is a medium-voltage 3-phase 4-wire system this type of indicator is not of general utility.

An ammeter in the earth connection of the neutral point of the system may indicate the approximate extent of a single-phase fault, but is useless to determine the amount of normal leakage on an incipient short-circuit. For example, it is possible for the fault resistance of a network to be below 1 ohm and the earth return current to be of the order of 3 amperes only.

The determination of the fault resistance on a single-phase network is not highly complicated, although more difficult than the corresponding d.c. case.

With a 3-phase 4-wire network, however, the difficulties are considerable. So far as is known, the only method hitherto described for dealing with this case completely is that due to Sahulka. Evaluation of the several equations is, however, extremely tedious; and, since the method involves the use of small differences in readings, the results are highly unsatisfactory even when sub-standard instruments are employed. Results cannot be obtained rapidly, and the method is altogether unsuitable for field use, although of considerable technical value.

A simple test advanced by Sahulka may be applied to indicate changes in the insulation of a network, provided the earth connection is broken. The method consists of connecting an electrostatic voltmeter between a conductor and earth, and then connecting a variable resistance between the same conductor and earth, the actual value of the rheostat being adjusted so as to decrease the voltmeter reading by a definite amount, say 10 per cent. The lower the insulation resistance, the lower the value of inserted resistance to effect the desired variation. Each phase should be dealt with in turn.

This method may be valuable in providing a rough guide to the state of a network, but it does not give the actual value of the fault resistance. The latter may, of course, be determined by the superimposition of a direct current from a battery, using a d.c. instrument, so arranged that it is unaffected by the passage of alternating current. Apart from the special filter circuits required, this necessitates either disconnection of the system from earth or the insertion of the apparatus in the earth connection, in which case the instrument carries the whole of the return current in addition to the small testing current. The conditions are therefore far from ideal, and are likely to result in trouble.

## THEORETICAL CONSIDERATIONS.

In view of the importance attaching to the periodical testing of vulcanized-bitumen mains, the question has been carefully investigated and the method described below devised.

Consider the general case of an unbalanced 3-phase 4-wire system having phase voltages $E_1$, $E_2$, $E_3$, with angular displacements of zero, $\phi_2$, and $\phi_3$ respectively. If the fault resistances of the four conductors are $r_1$, $r_2$, $r_3$, and $r_N$ respectively, their capacitances are

$C_1$, $C_2$, $C_3$, and $C_N$ respectively, and the network fault resistance is $x$; then, by definition,

$$\frac{1}{x} = \frac{1}{r_1} + \frac{1}{r_2} + \frac{1}{r_3} + \frac{1}{r_N}$$

In an insulated system, the voltage to earth of the several conductors is determined by the currents flowing through the leakage resistances and capacitances. If the neutral point is now solidly earthed (i.e. through a negligibly low impedance) the magnitude ($I$) and phase ($\phi_N$) of the current returning through the earth connection are similarly dependent on these characteristics. The component of this current in phase with $E_1$ is

$$\begin{aligned} I \cos \phi_N = {} & \frac{E_1}{r_1} + \frac{E_2}{r_2} \cos \phi_2 + \frac{E_3}{r_3} \cos \phi_3 \\ & + E_1 \omega C_1 \sin 0^\circ + E_2 \omega C_2 \sin \phi_2 + E_3 \omega C_3 \sin \phi_3 \quad (1) \end{aligned}$$

where $\omega = 2\pi \times$ frequency.

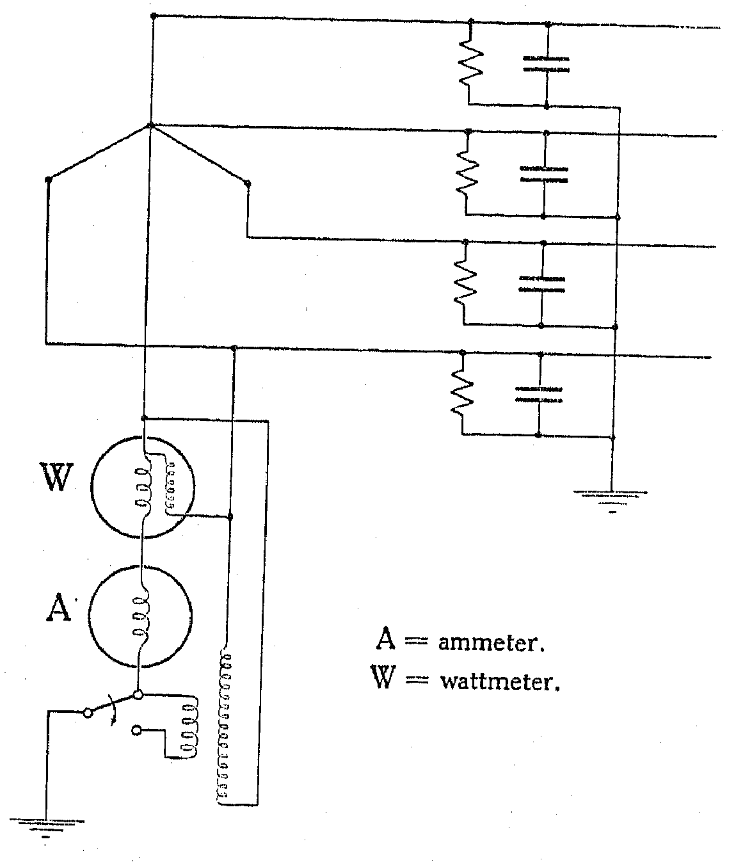

Fig. 1.—Fault-resistance measurement by wattmeter.

If now the voltage of the neutral point be raised above earth by an amount $E$ in phase with $E_1$, the in-phase component of the modified earth return current $I'$ will be given by

$$\begin{aligned} I' \cos \phi'_N = {} & \frac{E_1}{r_1} + \frac{E_2}{r_2} \cos \phi_2 + \frac{E_3}{r_3} \cos \phi_3 + E_1 \omega C_1 \sin 0^\circ \\ & + E_2 \omega C_2 \sin \phi_2 + E_3 \omega C_3 \sin \phi_3 \\ & + \frac{E}{x} + E\omega (C_1 + C_2 + C_3 + C_N) \sin 0^\circ \quad (2) \end{aligned}$$

Since $\sin 0^\circ = 0$, it follows that

$$I' \cos \phi'_N - I \cos \phi_N = E/x$$

$$\text{or} \quad x = \frac{E}{I' \cos \phi'_N - I \cos \phi_N} \quad . \quad (3)$$

This provides, therefore, a relatively simple method of determining the fault resistance of the system. The in-phase component of the neutral earth current may be simply determined by means of a wattmeter having the voltage coil energized from a supply in phase with, and proportional to, $E_1$. If the voltage conditions of the system are determined, the exact phase and magnitude of $I$ may be ascertained by resolving in a different direction (for example, in phase with $E_3$). As a check, the magnitudes of $I$ and $I'$ may be determined by means of an ammeter in the earth connection (see Fig. 1).

Further consideration indicates that certain other important conclusions may be deduced from the measurements. These are: (*a*) Since no assumptions have been made regarding equality of the phase capacitances, it is apparent that the method is independent of capacitance unbalance. (*b*) If, with the neutral point earthed, the component of $I$ in phase with the voltages $E_1$, $E_2$, and $E_3$, be separately determined, the largest positive value is obtained when using the phase of lowest resistance, assuming that the capacitance unbalance is not excessive. In the practical case, the capacitances do not differ by large amounts. (*c*) If the three in-phase components are small, but the fault resistance as finally ascertained is low, the neutral-conductor insulation is faulty. (*d*) If the voltage system is symmetrical, the individual values of conductor insulation resistance cannot be computed without additional measurements. (*e*) With an unbalanced system of voltages, the respective phase leakages may be derived; but the resulting formulæ are too complicated for practical application.

The important information available comprises the value of system fault-resistance, an indication as to which phase has the lowest insulation resistance, and information regarding the condition of the neutral conductor. These points cover the practical requirements adequately.

## Experimental Verification.

In order to verify the validity of the foregoing considerations before proceeding with the construction of a portable equipment, experimental model networks were employed in the laboratory: resistances of values varying from very low amounts up to 2 megohms, and condensers of from 0 to 10 microfarads, were used to represent the leakage paths of a 3-phase 4-wire network. In addition, an ammeter and the current coil of a wattmeter were inserted in the neutral-point connection, together with the 25-volt secondary winding of a small single-phase transformer: the primary winding of the transformer and the voltage coil of the wattmeter being connected to one phase and neutral of the supply as required. The neutral-to-earth voltage $E$ was also measured.

Ammeter readings $I$ and $I'$ and wattmeter readings $P$ and $P'$ were taken without and with the single-phase transformer winding in the neutral connection. It is apparent that $I \cos \phi_N = P/E_1$, and $I' \cos \phi'_N = P'/E_1$, whence

$$x = \frac{E}{\dfrac{P'}{E_1} - \dfrac{P}{E_1}} = \frac{EE_1}{P' - P} \quad . \quad . \quad . \quad . \quad (4)$$

Throughout the tests good agreement between measured and calculated values was obtained, with widely varying values of resistance and capacitance connected to the various conductors deliberately: considerable voltage unbalance also existed.

## PRACTICAL REQUIREMENTS.

Field tests later indicated that fault resistances of $0{\cdot}8$ ohm were not unknown, in which case additional neutral currents of $12{\cdot}5$ amperes would be produced by raising the distribution-system voltage to earth by 10 volts only. It was accordingly decided to employ a small transformer giving a secondary voltage of 10 volts, and capable of carrying 20 amperes continuously, the wattmeter current coil being similarly rated.

For routine testing, the number of readings should be reduced to a minimum, and the necessary calculations should be simplified. For a given excitation of the auxiliary transformer, the secondary voltage would only vary from the no-load value by an amount corresponding to the impedance drop during testing: this difference is very small in most cases, and for routine purposes may be disregarded. The rated output voltage may therefore be assumed equal to the neutral-to-earth voltage $E$, without serious error.

In order to maintain the excitation constant under varying voltage conditions, the primary winding is provided with a number of tappings at the higher-voltage end, the connection being altered by means of a plug contact. This winding is provided with an additional tapping at 150 volts, corresponding to the rated voltage of the wattmeter shunt winding; thus the wattmeter always operates at rated voltage or a definite fraction thereof obtained by means of a multiplier. A small voltmeter is also connected in parallel with the wattmeter voltage coil, the 150-volt indication being distinctively marked so as to facilitate correct setting of the tapping connection.

Formula (4), namely $x = EE_1/(P' - P)$, now reduces to $x = 1\,500/(P' - P)$, regardless of the actual phase voltage.

In order to obtain reasonable readings with high fault resistances, a low power-factor model wattmeter is employed, giving full-scale deflection under one-fifth of rated conditions. Since the readings may be either positive or negative, according to the phase of the earth return current, a centre-zero scale is employed. By means of a spring-controlled switch the current through the wattmeter voltage coil is adjusted to either $\frac{1}{4}$ or $\frac{1}{10}$ the rated value; thus the scale reading at rated volts may be reduced if necessary.

During the test previously described, the impedance of the auxiliary-transformer secondary winding is included in the neutral earthing connection in one case, but not in the other, so that conditions are slightly disturbed. By taking an additional reading $P''$ with the transformer secondary reversed, this disturbance is obviated. Using the reversed readings, $x=2EE_1/(P'-P'')$ very nearly.

If the fault resistance is required accurately, it is necessary to measure the actual value of $E$ (neutral to earth) and correct the readings accordingly. Under practical conditions, however, the error introduced by neglecting this factor is of minor importance.

## PORTABLE TESTING EQUIPMENT.

For regular testing, the several components are housed in a wooden cabinet measuring approximately 20 in. × 14 in. × 9 in. Three external connections only are required, namely conductors to earth and neutral respectively, and a flexible connection to the phase conductor: the latter carries a small current only. The arrangement is shown diagrammatically in Fig. 2.

In carrying out a test the neutral earthing connection of the supply system is disconnected, and the testing set is inserted with the " live " terminal connected to the neutral point and the " earth " terminal to earth. By means of a suitable link arrangement this may be done without removing the earth from the system. The third terminal is connected to one phase of the supply, and the primary tapping point varied until the voltmeter in the set reads approximately 150 volts.

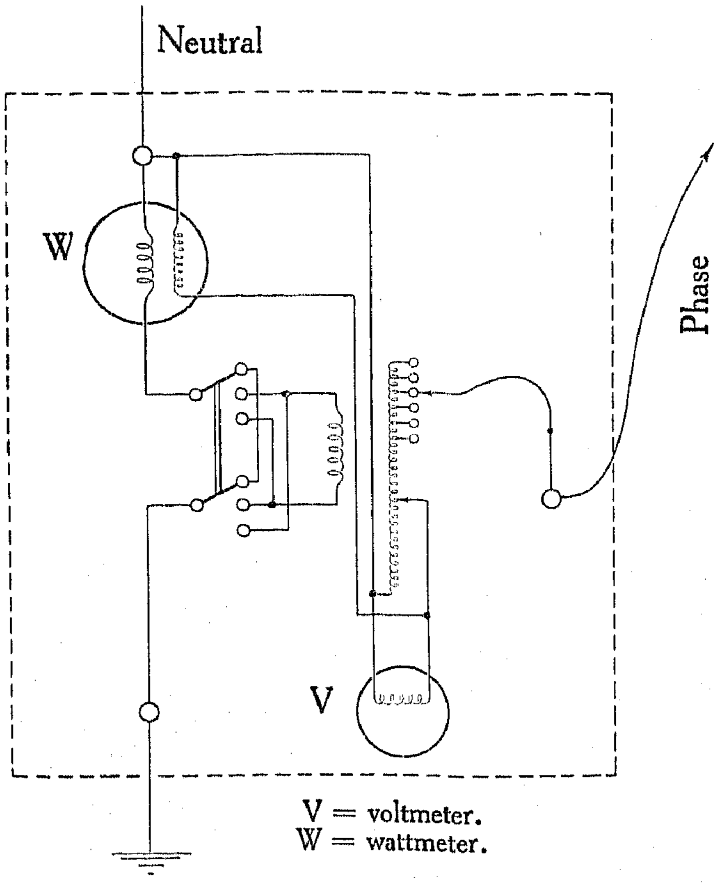

FIG. 2.—Fault-resistance tester.

The switch is normally in the " through " position: to obtain the necessary readings, the switch is moved first to position 2 and then to position 3, the wattmeter multiplier switch being suitably adjusted to give reasonably large deflections. Particular attention must be paid to the direction of deflection, and the appropriate sign must be applied before the result is calculated.

## CONCLUSIONS.

The principal advantages claimed for the method are: (*a*) It requires very little time or preparation. (*b*) The fault resistance is derived by the application of a simple formula. (*c*) The conductor of lowest insulation resistance is indicated by taking additional readings. (*d*) The method is independent of capacitance unbalance. (*e*) The method is independent of voltage unbalance or phase displacement. (*f*) The apparatus is adjustable for various voltages. (*g*) Supply is not interrupted. (*h*) The earth connection need not be interrupted. (*j*) The one condition for accuracy is that, whatever unbalance exists when the test is commenced, should continue; but as the whole test is completed in about 5 sec. no apprehension need arise on this score.

It is an advantage to place a short list of instructions in the lid of the completed instrument. The following list gives all the explanations required by the mains engineer; it obviously refers to the simpler test, i.e. with the auxiliary transformer inserted with one polarity only.

*Instructions as to Use of A.C. Fault Resistance Meter.*

(1) The instrument is for use only on a.c. circuits where the earth current does not exceed 20 amperes.

(2) Connect instrument terminals to earth and neutral respectively, with switch in " through " position.

(3) Insert plug connection into socket corresponding most nearly to the busbar voltage.

(4) Connect flexible lead to each phase in turn. If necessary, adjust plug connection until voltage indicator registers 150 volts. Note readings on main dial, and direction. The highest positive reading indicates the phase with lowest fault resistance.

(5) The main-dial readings are to be multiplied by 10.

(6) To increase readings, turn multiplier switch. The main-dial readings are now to be multiplied by 4.

(7) To increase readings further, turn switch to position 1. Readings are now direct.

(8) Re-connect flexible lead to one phase with switch in " through " position, taking reading $P$.

(9) Place switch in " test " position, and take reading $P'$.

(10) Calculate fault resistance from formula

$$x = \frac{1\,500}{P' - P}$$

It is important to note that the readings are to be applied with the correct sign.

(11) If the phase deflections obtained in (4) are small, but the fault resistance calculated by (10) is low, the neutral-conductor insulation is faulty.

Acknowledgment is made to Mr. H. C. Lamb, chief engineer and manager of the Manchester Corporation Electricity Department, who instigated these investigations, for permission to publish this description.

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# THE OPERATION OF SUPERHETERODYNE FIRST-DETECTOR VALVES.*

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[Communication from the Research Staff of the M.O. Valve Co., Ltd., Wembley.]

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Summary.

The equivalent anode circuit of a superheterodyne first-detector valve is derived, and the fundamental circuit constants (conversion conductance and effective anode a.c. resistance) are defined. Mathematical analysis leads to a method of measuring effective anode a.c. resistance and five methods of measuring conversion conductance, all of which are described in some detail. Graphs are included to illustrate these methods and show the degree of agreement between them.

## (1) Types of First Detectors.

With the increasing popularity of superheterodyne receivers it has become important to have some numerical criterion of the performance of the first-detector or frequency-changing stage. In this paper it will be shown that such a circuit is analogous to an amplifying stage and possesses an equivalent circuit similar to that of the corresponding amplifier.

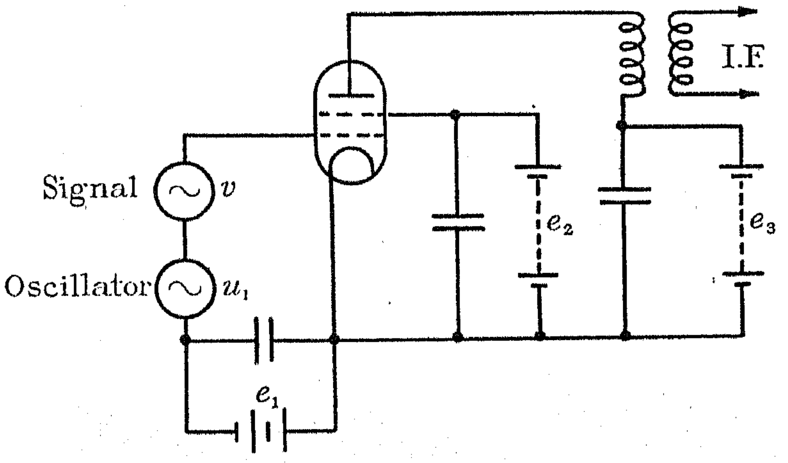

Fig. 1a.

The first detector in a superheterodyne receiver is ideally an arrangement whereby an incoming signal of one frequency (signal frequency) is converted into a signal of another frequency (intermediate frequency) in such a fashion that a linear relationship is maintained between the amplitudes of these two signals. This effect is obtained by the use of a local oscillator of such a frequency that the intermediate frequency is equal to the difference between the oscillator and signal frequencies, and some form of mixing device in order to produce the required difference frequency. A thermionic valve is generally used for this purpose, and the frequency-changing may be accomplished in one of the following ways:—

(*a*) Signal and oscillator inputs are injected in series between the cathode and control grid, and the i.f. (intermediate-frequency) output developed across a tuned circuit in the anode circuit. This method depends for its effectiveness on the curvature of the $e_g$, $i_a$ characteristics of the valve. The methods of grid injection and of cathode injection (shown diagrammatically in Figs. 1a and 1b respectively) are practically equivalent: the fact that there is a p.d. (potential difference) of oscillator frequency between cathode and screen—or cathode and anode—in the case of cathode injection is unimportant, owing to the fact that the screen-anode mutual conductance and anode a.c. conductance are small compared with the grid-anode mutual conductance of the valve.

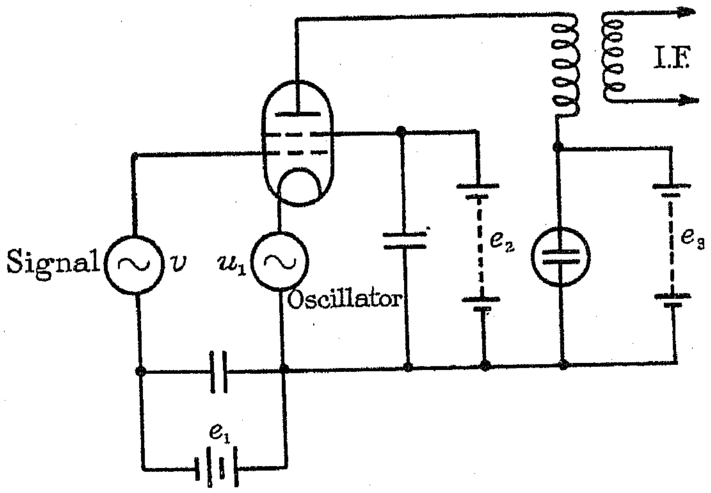

Fig. 1b.

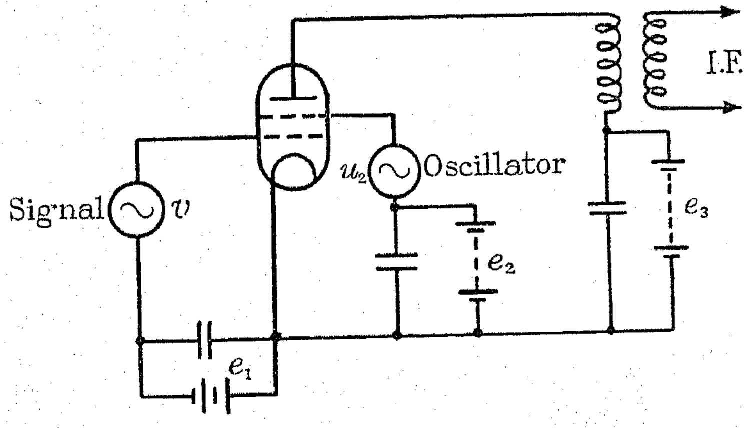

Fig. 2.

(*b*) Signal and oscillator inputs are applied to two different grids of a multi-electrode valve and the i.f. output taken from the anode circuit as before. The case of screen injection in a screen-grid tetrode is shown in Fig. 2.

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(*c*) The signal input is applied to the control grid and the oscillator input to the anode, the i.f. output being also taken from the anode circuit (Fig. 3).

In cases (*b*) and (*c*), non-linearity of the characteristics is not essential except so far as the potential of one electrode controls the mutual conductance between another pair.

### (2) CONVERSION CONDUCTANCE.

When relatively small signals, such as those normally encountered in practice, are applied to the first detector valve, and the external anode impedance is zero at intermediate frequency, the ratio (i.f. current in anode circuit)/(signal-frequency potential on grid) is approximately constant (rigidly so in the ideal case), and its limiting value as the input tends to zero is defined as the conversion conductance or transfer conductance. The former name appears preferable as it emphasizes the frequency-changing property and cannot lead to confusion with the transfer conductance as used in line theory. Conversion conductance is analogous to the mutual conductance of an amplifier valve and will be denoted by $g_t$. It is a function of the local oscillator voltage and of the mean working potentials of the electrodes of the valve.

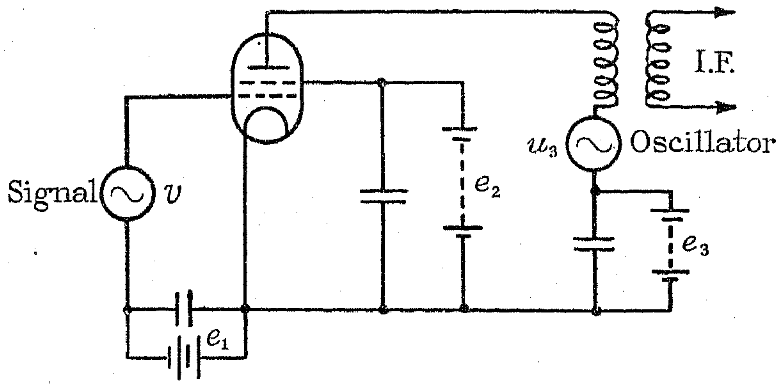

FIG. 3.

### (3) RELATIONSHIP OF CONVERSION CONDUCTANCE TO THE VALVE CHARACTERISTICS.

This theory may be developed in several ways, of which only the simplest will be discussed here. Other methods, amounting respectively to a Fourier analysis of the output current, a Taylor-series expansion of the valve characteristics,* and a straightforward power-series expansion, lead to several interesting formulæ but are not included in this paper on account of their relative mathematical complexity.

The principal results here obtained (i.e. those contained in equations 4 and 5) have been previously obtained by Peterson and Llewellyn,† who, however, resort to a power-series method and deal only with the case where oscillator and signal inputs are applied to the same electrode. The result of equation (6) is, to the best of the author's knowledge, new, although a similar result has been obtained for one particular case by Appleton and Taylor ‡ in an early paper discussing heterodyne reception.

In the following analysis the anode current $i_a$ will be regarded as represented by $F(v_1, v_2, v_3)$, where $F$ is any (continuous) function of the electrode potentials $v_1, v_2, v_3$, of the detector valve; and $v_1$ = potential of signal grid, $v_2$ = potential of another control electrode, $v_3$ = potential of anode.

Let the signal input be $v \cos \omega_s t = v \cos \phi$, and suppose, for the sake of generality, oscillator inputs $u_1 \cos \theta$, $u_2 \cos \theta$, $u_3 \cos \theta$ $(\theta = \omega_0 t)$ injected into the three electrodes. Any of the cases mentioned in Section 1 may be obtained by equating two of the quantities $u_1, u_2, u_3$, to zero. $\theta$ and $\phi$ are used in place of $\omega_0 t$ and $\omega_s t$, for convenience in notation.

Now let the components of anode current $(i_a)$ be $A_{rs} \cos (r\theta + s\phi)$ = component of pulsatance $(r\omega_0 + s\omega_s)$, where $r$ may take all integral values from 0 to $+\infty$ and $s$ all positive or negative integral values, including zero. Thus

$$\begin{aligned} i_a &= F[v_1, v_2, v_3] \\ &= F\big[e_1 + u_1 \cos \theta + v \cos \phi,\ e_2 + u_2 \cos \theta, \\ &\qquad e_3 + u_3 \cos \theta - RA_{1(-1)} \cos (\theta - \phi)\big] \quad . \qquad (1) \end{aligned}$$

if the anode load is assumed to be of resistance $R$ at the difference frequency and of negligible impedance at other frequencies. Also,

$$\frac{\partial i_a}{\partial v} = \cos \phi \frac{\partial i_a}{\partial e_1} - R \frac{\partial A_{1(-1)}}{\partial v} \cos (\theta - \phi) \frac{\partial i_a}{\partial e_3}$$

since $\partial F/\partial v_1 = \partial i_a/\partial e_1$, $\partial F/\partial v_3 = \partial i_a/\partial e_3$, and $A_{1(-1)}$ is a function of $v$.

Now take the coefficient of $\cos (\theta - \phi)$ on both sides:—

$$\frac{\partial A_{1(-1)}}{\partial v} = \tfrac{1}{2}\frac{\partial A_{10}}{\partial e_1} + \tfrac{1}{2}\frac{\partial A_{1(-2)}}{\partial e_1} - R\frac{\partial A_{1(-1)}}{\partial v}\left[\frac{\partial A_{00}}{\partial e_3} + \tfrac{1}{2}\frac{\partial A_{2(-2)}}{\partial e_3}\right]$$

or

$$\frac{\partial A_{1(-1)}}{\partial v} = \left[\tfrac{1}{2}\frac{\partial A_{10}}{\partial e_1} + \tfrac{1}{2}\frac{\partial A_{1(-2)}}{\partial e_1}\right] \Big/ \left[1 + R\left(\frac{\partial A_{00}}{\partial e_3} + \tfrac{1}{2}\frac{\partial A_{2(-2)}}{\partial e_3}\right)\right] \qquad (2)$$

For the case of an ordinary amplifier valve with input $v \cos \phi$ and load resistance $R$, the output current $A_{01} \cos \phi$ is given by

$$\lim_{v \to 0} \frac{\partial A_{01}}{\partial v} = \frac{g_m}{1 + g_a R} \quad . \quad . \quad . \quad . \qquad (3)$$

where $1/g_a = R_a$ = anode a.c. resistance.

Hence, comparing (2) and (3) and replacing $g_m$ by $g_t$ (the conversion conductance) and $g_a$ by $g_e$ (the reciprocal of the effective anode a.c. resistance of the detector valve), we get

$$g_t = \lim_{v \to 0} \left[\tfrac{1}{2}\frac{\partial A_{10}}{\partial e_1} + \tfrac{1}{2}\frac{\partial A_{1(-2)}}{\partial e_1}\right] = \tfrac{1}{2}\left[\frac{\partial A_{10}}{\partial e_1}\right]_{v=0} \cdot \qquad (4)$$

since $A_{1(-2)}$ vanishes with $v$; and

$$g_e = \lim_{v \to 0} \left[\frac{\partial A_{00}}{\partial e_3} + \tfrac{1}{2}\frac{\partial A_{2(-2)}}{\partial e_3}\right] = \left[\frac{\partial A_{00}}{\partial e_3}\right]_{v=0} \cdot \qquad (5)$$

Interpreted physically, equation (4) shows that the conversion conductance of a stage is given by one-half of the slope of the (oscillator-frequency output current)/(control-grid volts) curve, with the normal electrode potentials and oscillator input but no signal-frequency input. The effective anode a.c. conductance is seen from equation (5) to be given by the slope of the (mean anode current)/(anode volts) curve with the valve operating as described immediately above. It is to be noted that these results are quite independent of the mode of injection of the oscillator voltage and are applicable in the case of multi-electrode valves where the oscillator-frequency input may be applied to two or more electrodes. The same formulæ apply also to the case of detector-oscillator valves, which may have the appropriate measurements made on them while actually oscillating.

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* See Reference (1). † *Ibid.*, (2). ‡ *Ibid.*, (3).

The case of grid injection admits of special treatment. We have, if $R = 0$,

$$\partial i_a/\partial u_1 = \cos\theta\,\partial i_a/\partial e_1$$

whence, equating constant terms,

$$\partial A_{00}/\partial u_1 = \tfrac{1}{2}\partial A_{10}/\partial e_1$$

so that, by (4),

$$g_t = \left[\frac{\partial A_{00}}{\partial u_1}\right]_{v=0} \quad . \quad . \quad . \quad . \quad (6)$$

The physical implications of this should be evident, especially when the similarity of this method of frequency-conversion to normal anode-bend detection is realized.

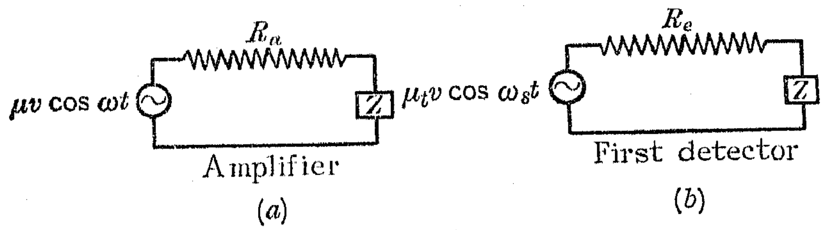

FIG. 4.

### (4) EQUIVALENT ANODE CIRCUIT.

As shown in Section 3, the first detector valve is analogous to an ordinary amplifier valve with $g_m$ replaced by $g_t$, and $R_a(=1/g_a)$ by $R_e(=1/g_e)$. Fig. 4 shows this analogy in detail. The practical differences between the two cases lie in the frequency-change involved in the first detector and in the different methods of measurement of the circuit constants.

### (5) EFFECT OF PHASE DIFFERENCES AND INTER-ELECTRODE CAPACITANCES.

No loss of generality is incurred by the use of cosines only in the above analysis, as this is merely equivalent to an arbitrary choice of zero time instant. The difference frequencies are representable entirely by cosine terms provided no phase changes are introduced; with the tuned anode circuits normally employed, the anode current at resonance is exactly in phase with the control-grid voltage. The phase-shifting effect of inter-electrode capacitances is automatically compensated for by the tuning of the anode circuit. The coupling effect of the inter-electrode capacitances is small, on account of the fact that the circuits associated with the various electrodes are in general tuned to different frequencies and are of relatively low impedance at the other frequencies concerned.

### (6) MEASUREMENT OF EFFECTIVE ANODE ALTERNATING-CURRENT RESISTANCE.

Equation (5) leads directly to an experimental method of determining $R_e$. The mean anode current is plotted against the mean anode potential with the oscillator switched on, or its equivalent—an audio-frequency or radio-frequency input—applied between the normal oscillator input terminals. The only precautions to be observed are that the anode and screen by-pass condensers should be of negligibly low impedance at the test frequency. The effective anode a.c. resistance (the so-called conversion impedance) is the reciprocal of the slope of the dynamic (anode volts)/(anode current) curves obtained as described above; it is analogous to the ordinary anode a.c. resistance derived from the corresponding static curves.

### (7) MEASUREMENT OF CONVERSION CONDUCTANCE.

Apart from the direct method of applying two inputs corresponding to the signal and oscillator inputs and measuring the difference-frequency outputs, there are four methods of measuring conversion conductance which have been developed from the mathematical analysis of Section 3. All five methods will be described in some detail.

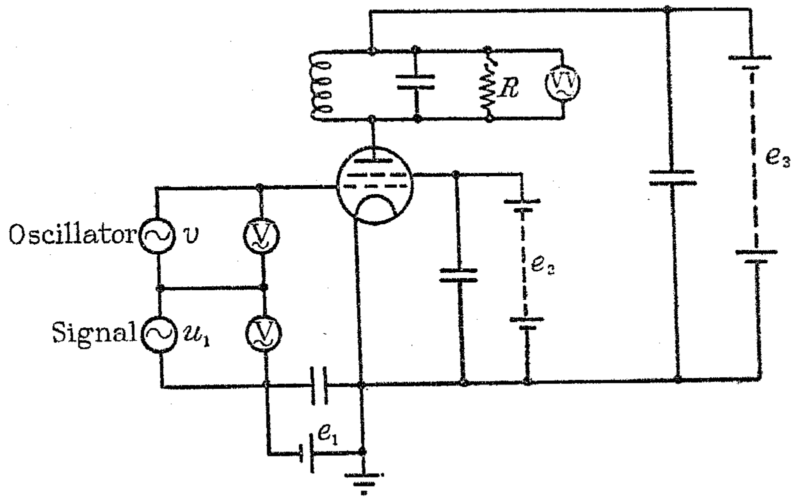

FIG. 5.

#### (a) *Direct Method.*

Fig. 5 shows a schematic circuit diagram for this method, using a screen-grid valve as detector. The two high-frequency inputs corresponding to local oscillator and signal are injected either in series in the control-grid circuit [Section 1, case (*a*)] or in the screen or anode and control-grid circuits respectively [Section 1, cases (*b*) and (*c*)]. Both of these input voltages are measured by known methods (e.g. thermocouple and injector resistance, or valve voltmeter). On the output side, in order to separate the required difference-frequency output from the other components of the anode current, it is necessary to use a tuned circuit; in actual practice it has been found necessary to use a transformer with both primary and secondary tuned. In this case the ratio of primary to secondary voltage under operating conditions must be known. This ratio can easily be determined experimentally.

For the measurement of conversion conductance it is unnecessary to know either the anode a.c. resistance of the valve or the dynamic resistance of the anode tuned circuit. The conversion gain, namely the ratio of the i.f. voltage across the tuned primary of the i.f. transformer to the input signal voltage, is measured. Let it be $m_0$. Then the primary of the transformer is shunted by a resistance $1/g$ and the new conversion gain $m$ measured.

We have $g_t =$ conversion conductance, $g_e =$ anode a.c. conductance $= 1/R_e$, $g_d =$ dynamic conductance of load, and $g =$ conductance of shunt; so that the conductance of the shunted load is $(g_d + g)$.
Then

$$m_0 = g_t/(g_d + g_e) \quad . \quad . \quad . \quad . \quad (7)$$

and

$$m = g_t/(g_d + g_e + g)$$

Hence, eliminating $g_d + g_e$, we get

$$g_t = \frac{m_0 m}{m_0 - m} g \quad . \quad . \quad . \quad . \quad . \quad (8)$$

The shunt resistance should be of the same order of magnitude as the dynamic resistance of the tuned circuit, and may conveniently take the form of one of the varieties of metallized or moulded resistances now on the market.

If it should be required to measure $R_e$ by this method, equation (7) leads directly to the value

$$\frac{1}{R_e} = g_e = \frac{g_t}{m_0} - g_d$$

so that $R_e$ can be found provided $g_d$ is known.

In measuring $m_0$ and $m$ it is advisable to take the precaution of plotting i.f. output against signal input and to find the conversion gain from the initial linear portion of the curve.

### (b) *Dynamic " Fundamental Output " Method.*

In this case only one sinusoidal input is applied to the valve, and the actual output current is measured. A known fixed audio-frequency voltage, corresponding in amplitude to the oscillator input, is applied between the electrodes where the oscillator voltage normally exists. Instead of a voltage being applied corresponding to the signal input, the steady potential of the signal electrode is varied and the change in the fundamental frequency component of the anode current measured. Under these conditions, the conversion conductance is given (see equation 4) by

$$g_t = \tfrac{1}{2}\frac{\text{Change in peak fundamental component of anode current}}{\text{Change in potential of signal electrode}}$$

This applies to all the cases considered in Section 1.

It is important that only the fundamental component of the anode current be measured. In practice a simple 2-stage low-pass filter is sufficient at audio frequencies. The characteristic impedance of the filter should be low compared with the anode a.c. resistance of the valve, since the conversion conductance is supposed to be measured under conditions of constant anode potential. It is the difficulty of constructing such filters of low impedance for use at radio frequencies which has led to these tests being conducted at audio frequencies.

The actual circuit used is shown in Fig. 6 for the case of grid injection. The output from a low-frequency oscillator (600 cycles per sec.) is passed through a low-pass filter and, in series with the appropriate d.c. voltage, is applied to the oscillator electrode of the detector valve under test. The output from this valve is applied to the input of a second filter. Both filters have a characteristic impedance of 600 Ω and a cut-off frequency of 800 cycles per sec.; so that currents of the harmonics of the test frequency are cut off by the filters.

Filter 2 is terminated by 1 000 Ω on the input side and by its characteristic impedance, 600 Ω, on the output side. This latter resistance is made up of a resistance $r$ and an a.c. milliammeter (which may be either a thermal or a rectifier instrument), a blocking condenser of 10 μF being added in series in order to eliminate the d.c. component. The filter and terminating circuits were calibrated and the ratio of input to output current determined, so that from the a.c. milliammeter reading the value of the fundamental component of anode current could be calculated.

In practice, two methods of taking the observations have been followed. In the first, fundamental (peak) output current has been plotted against control-grid bias, for different values of the oscillator voltage (see Fig. 7). Half of the value of the slope of these curves (determined graphically) gives the conversion conductance (Fig. 8). The contour line corresponding to the points at which grid current commences to flow can be drawn on these curves and it is not practicable for the operating point to pass above this line, owing to the resultant increased damping of the input tuned circuit. It will be observed that the curves of Fig. 7 are concave upwards, so that the maximum conversion conductance is obtained just before grid current flows. It therefore becomes possible to plot an " optimum " curve showing conversion conductance against oscillator voltage with the control-grid bias voltage so adjusted that grid current just does not flow when any arbitrarily small input signal is applied. Fig. 9 gives an example of such curves, which are of great practical utility. A family of these curves may be drawn with any of the other valve constants as parameter, e.g. in this case curves are drawn corresponding to two different values of the screen voltage.

The fact that the curves of Fig. 7 (fundamental output current against control-grid potential) are approximately straight lines where they cross the grid-current contour line, leads to the second and quicker method of attack. For any given oscillator input voltage, the fundamental peak output current is measured with the control-grid potential adjusted so that grid current just does not flow. The control-grid bias is then increased by a known small quantity and the fundamental output current again measured. From the difference between these two readings the slope of the corresponding curve can be calculated, and half of this value gives the conversion conductance.

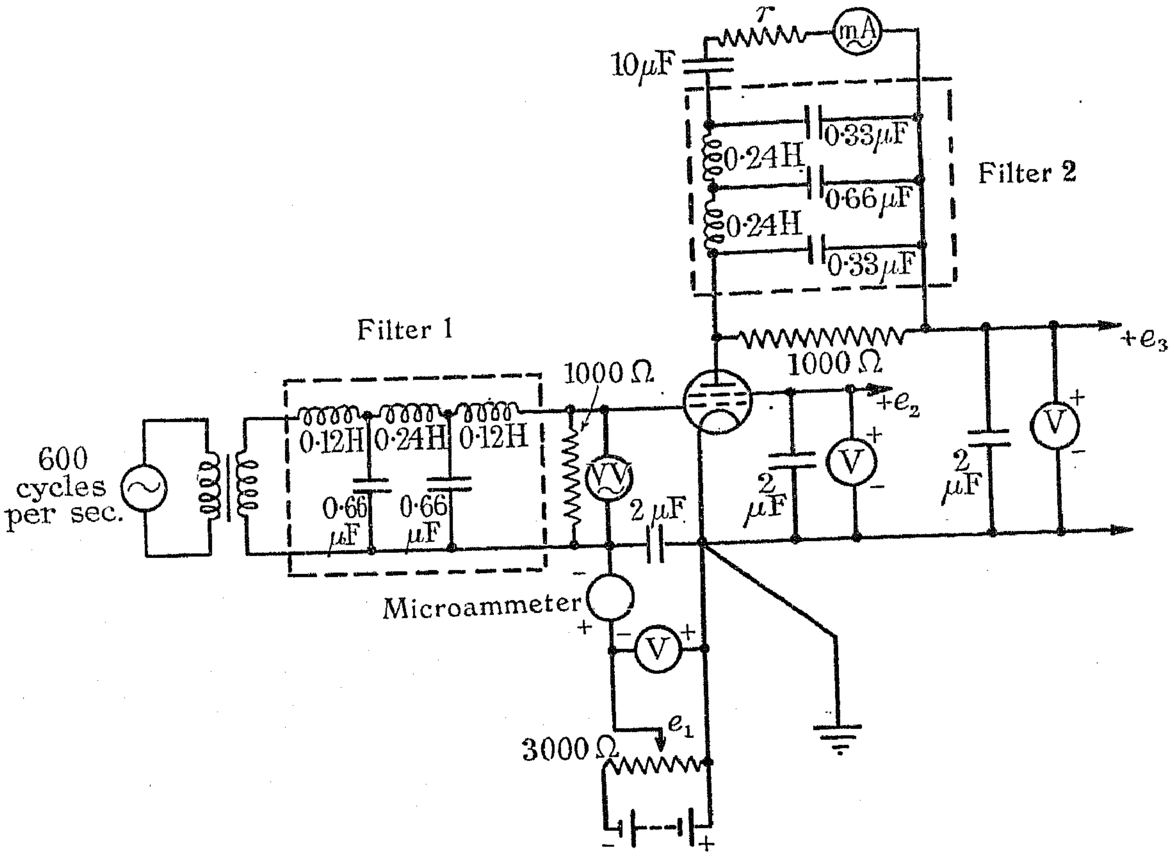

FIG. 6.

### (c) *Dynamic "Mean Anode Current" Method.*

This method is applicable only in the case where both oscillator and signal inputs are applied between the one pair of electrodes, i.e. for grid or cathode injection. It consists in plotting the mean anode current against oscillator input peak voltage for a series of different values of grid bias, as in Fig. 10. The oscillator input may be either audio- or radio-frequency; the one point of importance is that the a.c. return paths (i.e. bypass condensers) from anode and screen to cathode must be of low impedance at the test frequency employed.

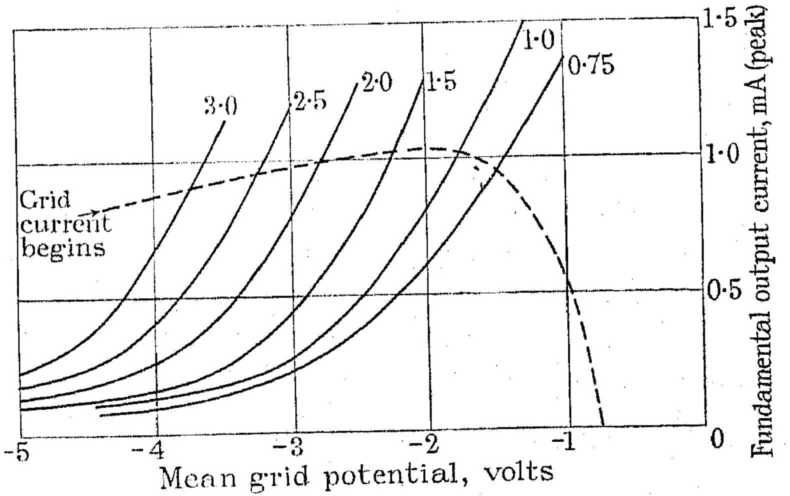

FIG. 7.

Numbers on curves denote oscillator peak volts.

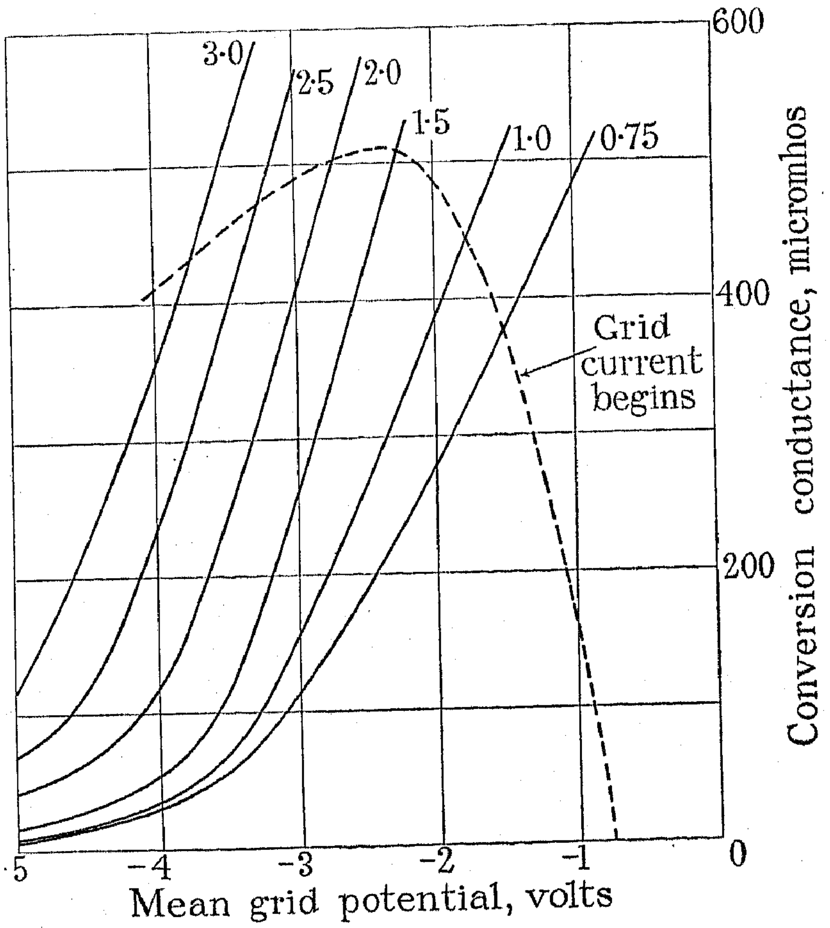

FIG. 8.

Numbers on curves denote oscillator peak volts.

The gradient of the above curves gives the conversion conductance, in virtue of equation (6). As before, the contour line for the commencement of grid current may be drawn on these curves, and, as appears in Fig. 10, the maximum values of conversion conductance are obtained where the curves cross the grid-current line. The conversion-conductance curves corresponding to Fig. 10 are shown in Fig. 9 and should be compared with the results of method (*b*) in the same graph.

### (*d*) *Graphical Method.*

$$\frac{\partial A_{10}}{\partial e_1} = \frac{\partial}{\partial e_1}\,(\text{coefficient of } \cos\theta \text{ in } i_a),$$

$$= \text{coefficient of } \cos\theta \text{ in } \partial i_a/\partial e_1,$$

$$= \text{coefficient of } \cos\theta \text{ in } g_m,$$

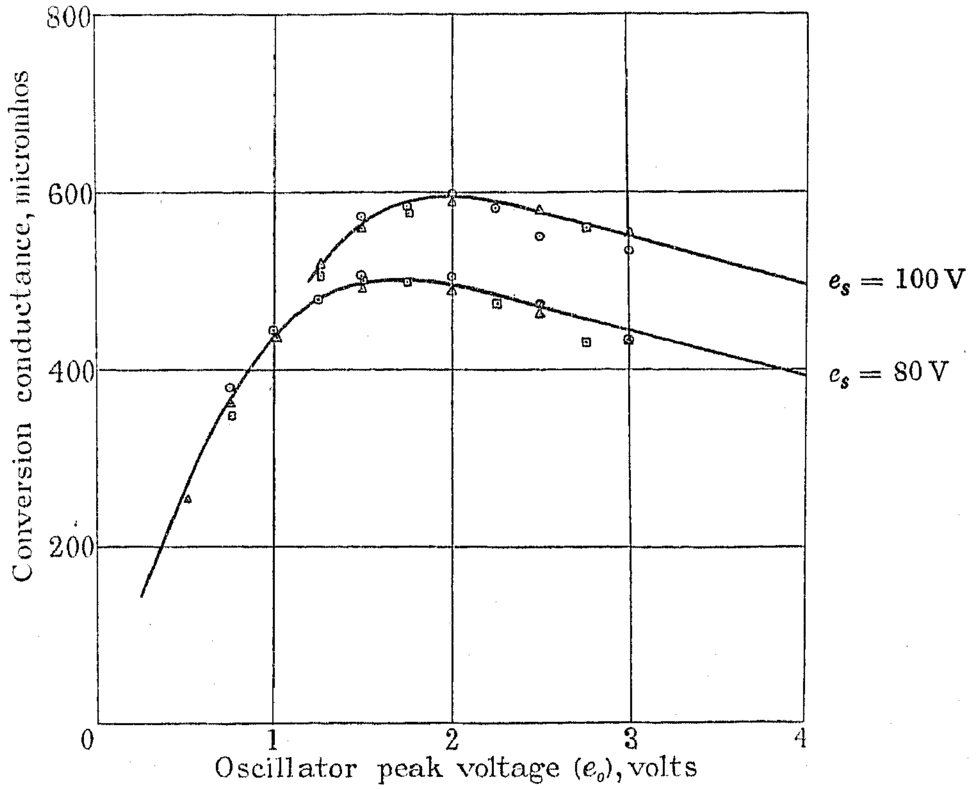

FIG. 9.

⊙ Method (*b*) (fundamental output). △ Method (*d*) (graphical).
⊡ Method (*c*) (mean anode current). D.C. bias voltage = $-(e_0 + 0\cdot 75\ \text{V})$.

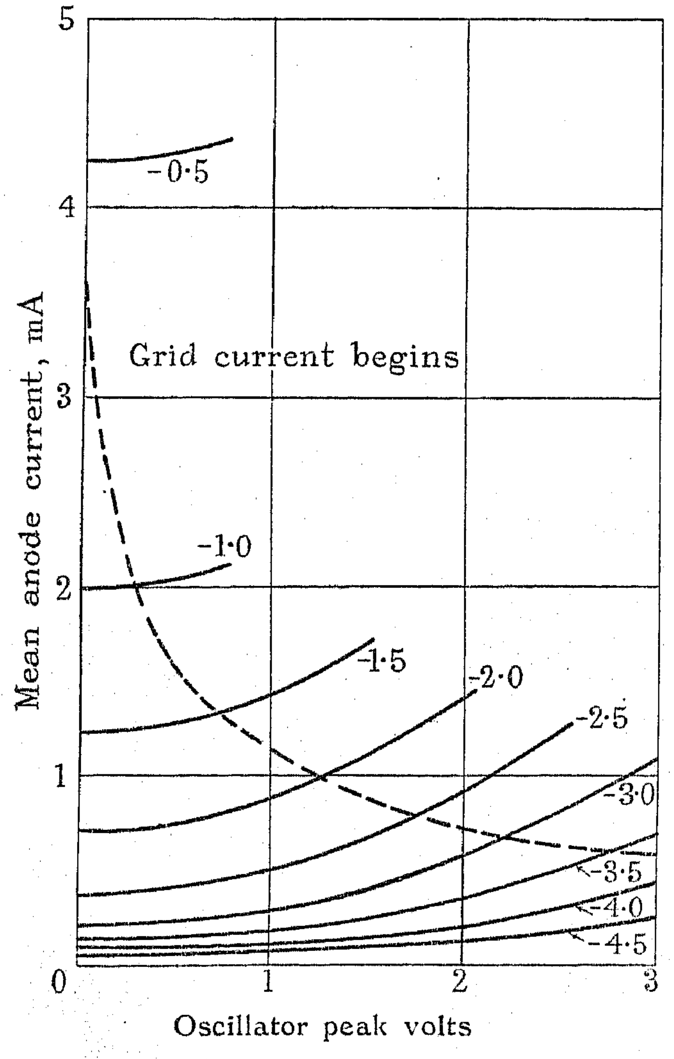

FIG. 10.

Numbers on curves denote control-grid bias.

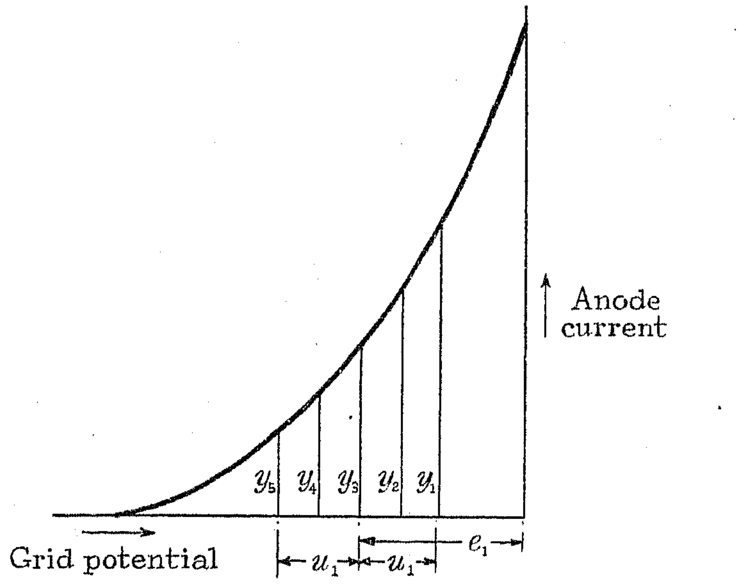

FIG. 11A.

Fundamental peak output current = $\frac{1}{3}(y_1 + y_2 - y_4 - y_5)$.

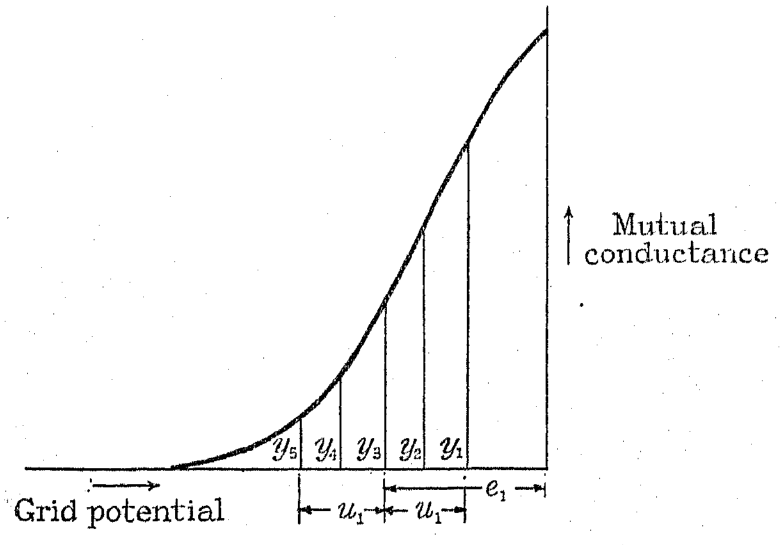

FIG. 11B.

Conversion conductance = $\frac{1}{6}(y_1 + y_2 - y_4 - y_5)$.

where $g_m$ (the mutual conductance of the valve) is regarded as a function of $\theta$ for any given oscillator input. In the case of grid injection and no anode load, $\theta$ occurs only in the value of $v_1$, and hence $g_m$ is a function of $v_1$ only; $g_m = f(v_1)$, say.

When $v = 0$ (i.e. there is no signal input)

$$g_m = f(e_1 + u_1 \cos \theta)$$

and the coefficient of the term in $\cos \theta$ may be obtained graphically from the $e_1$, $g_m$ curve, just as the fundamental output current may be obtained from the $e_1$, $i_a$ curve.

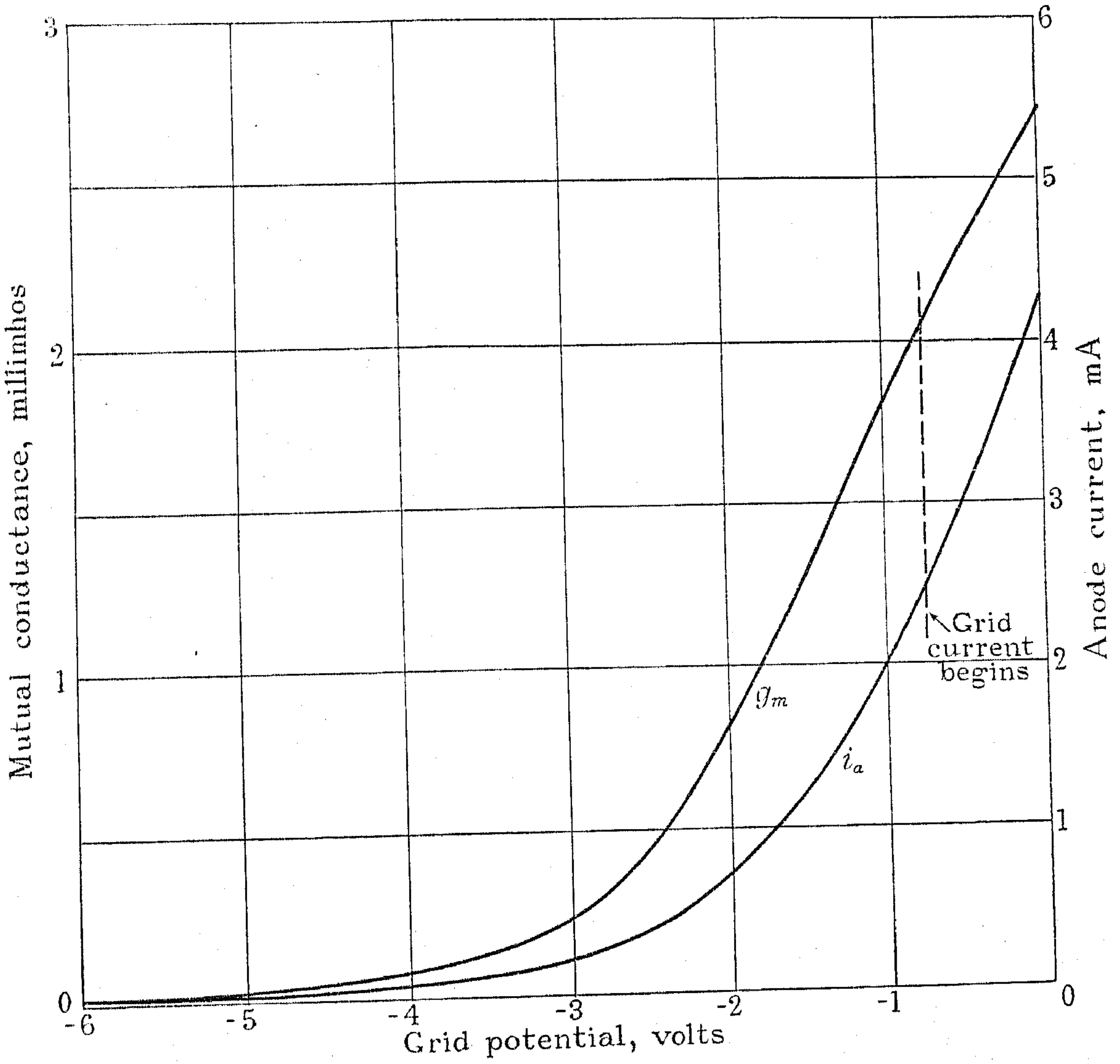

FIG. 12.

Now, by equation (4),

$$g_t = \frac{1}{2}\left[\frac{\partial A_{10}}{\partial e_1}\right]_{v=0} = \tfrac{1}{2}(\text{Coefficient of } \cos\theta \text{ in } g_m) \qquad (9)$$

as determined above. This method is illustrated in Figs. 11A and 11B, a 5-ordinate scheme of analysis being used for the purposes of this description.

Fig. 12 shows the $e_g$, $i_a$ and $e_g$, $g_m$ curves for the valve used to demonstrate methods (*b*) and (*c*), and the resulting values of $g_t$ determined by the graphical method are plotted in Fig. 9. In this case, as before, the grid-bias voltage was made as small as possible, without allowing the operating point to pass into the region of grid current.

It has been found experimentally that the $e_g$, $i_a$ characteristics of most of the screen-grid and high-frequency pentode valves tested so far are approximately parabolic over the useful range, so that the $e_g$, $g_m$ curves are almost linear. The case of truly linear $e_g$, $g_m$ curves is capable of mathematical analysis,* and Fig. 13 shows the conversion conductance (as a fraction of the mutual conductance $g_0$ when grid current is just commencing) plotted against oscillator peak voltage (as a fraction of the interval $a$ in $e_g$ between the point of commencement of grid current and the point at which $g_m = 0$). The maximum value of $g_t$ is $0 \cdot 268\, g_0$, and this occurs with an oscillator peak voltage of $0 \cdot 65a$. These figures agree well with those found in practice.

### (*e*) *Dynamic "One Frequency" Method.*

If a.c. voltages corresponding in magnitude to the oscillator and signal inputs, but of the same frequency, are applied between the appropriate electrodes, the difference-frequency is zero and hence it follows that the conversion conductance can be determined from the change in mean anode current as the signal input is varied.

If $R = 0$ and $\phi = \theta - \alpha$, we have, as in Section 3,

$$\partial i_a / \partial v = \cos \phi \, \partial i_a / \partial e_1 = \cos (\theta - \alpha) \partial i_a / \partial e_1.$$

Therefore, equating constant terms,

$$\partial A_{00} / \partial v = \tfrac{1}{2} \cos \alpha \, \partial A_{10} / \partial e_1.$$

---

* See Appendix.

Hence, by equation (4),

$$g_t = \tfrac{1}{2}\left[\frac{\partial A_{10}}{\partial e_1}\right]_{v=0} = \sec\alpha \left[\frac{\partial A_{00}}{\partial v}\right]_{v=0} \quad . \quad . \quad (10)$$

Applying this method experimentally, it is convenient to make $\alpha$ either 0° or 180°, in which case equation (10) may be written

$$g_t = \left[\frac{\partial A_{00}}{\partial v}\right]_{v=0}$$

$v$ being considered positive for $\alpha = 0°$ and negative for $\alpha = 180°$. The mean anode current may be plotted against $v$ and the gradient of this curve at $v = 0$ measured. A useful approximate method is to make $v$ any small voltage—0·5 volt (peak), say—and either (*a*) measure the change $\delta A_{00}$ in $A_{00}$ when $v$ is switched on, or (*b*) measure the change in $A_{00}$ when the phase of $v$ is reversed. In case (*a*), $g_t = \delta A_{00}/v$; and in case (*b*), $g_t = \delta A_{00}/(2v)$.

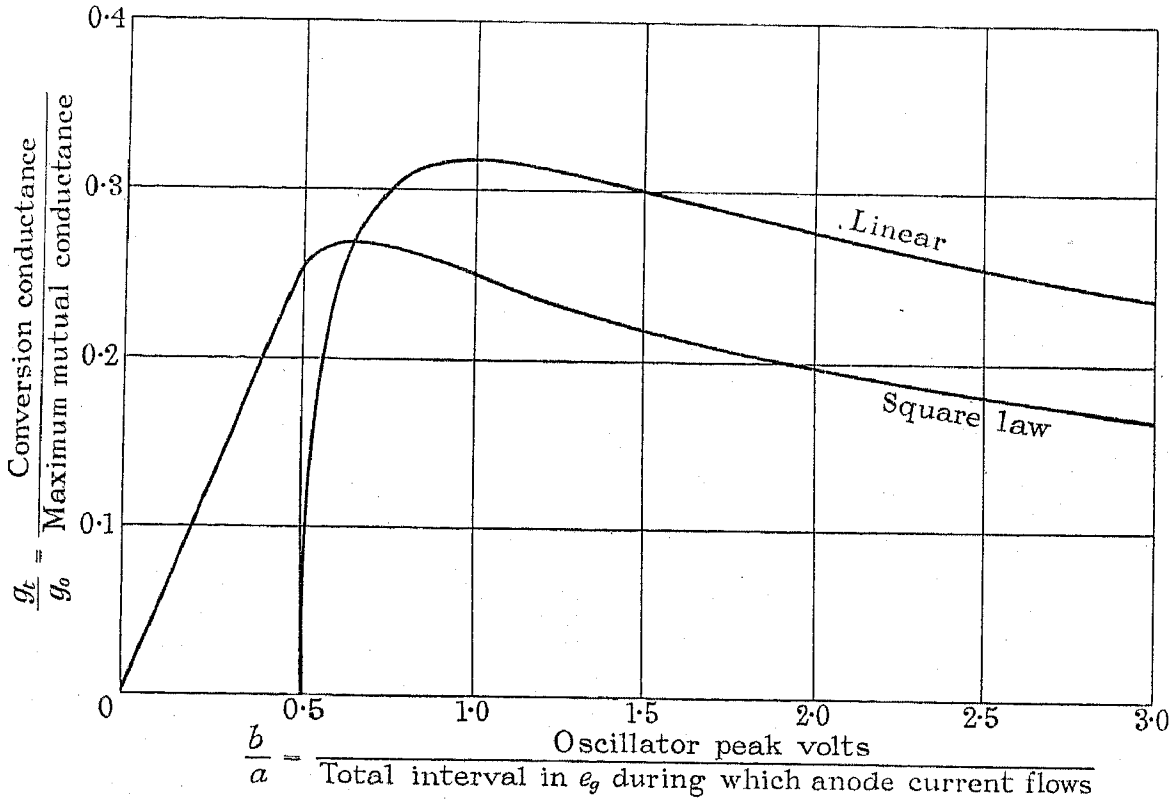

FIG. 13.

Any frequency, radio or audio, or even 50-cycle mains frequency, may be used in connection with this method.

### (8) COMPARISON OF METHODS OF MEASURING CONVERSION CONDUCTANCE.

Methods (*b*) and (*c*), Section 7, appear to be capable of the greatest accuracy. The "mean anode current" method (*c*) is subject to the limitation that it is only applicable to the case of grid or cathode injection. The graphical method (*d*) is subject to the limitations of all graphical methods; it is mainly of use where experimental methods cannot be carried out. The above three methods have no a.c. signal input and therefore may be regarded as derived methods. This in no way detracts from their accuracy, especially as conversion conductance is defined for vanishingly small values of signal input.

The direct method (*a*) and the "one frequency" method (*e*) bear certain resemblances to each other. The former is somewhat tedious and careful work is necessary if accurate results are to be obtained, but the results may be more convincing since the valve is being operated under conditions very similar to those occurring in practice. This psychological advantage is, however, more than balanced by the ease, speed, and accuracy, with which the other methods may be carried out.

Method (*e*) is probably the most suitable for routine testing and is being adopted for that purpose, using 50-cycle inputs, with a backed-off microammeter employed to measure small changes in anode current. It is capable of some degree of accuracy, provided the value of $v$ is kept small.

The author desires to tender his acknowledgments to the General Electric Co. and the Marconiphone Co. on whose behalf the work was done which has led to this publication. The "one frequency" method (*e*) is due to Messrs. A. H. Cooper and R. E. Spencer, of Electrical and Musical Industries, Ltd., and the author desires to express his thanks for permission to publish a description of this method along with the others.

## REFERENCES.

(1) A. C. BARTLETT: "The Calculation of Modulation Products," *Philosophical Magazine*, 1933, vol. 16, p. 845.

(2) E. PETERSON and F. B. LLEWELLYN: "The Operation of Modulators, from a Physical Viewpoint," *Proceedings of the Institute of Radio Engineers*, 1930, vol. 18, p. 38.

(3) E. V. APPLETON and MARY TAYLOR: "On Optimum Heterodyne Reception," *ibid.*, 1924, vol. 12, p. 277.

## APPENDIX.

### CONVERSION CONDUCTANCE FOR SQUARE-LAW CHARACTERISTIC (CATHODE INJECTION).

Let the $e_g$, $i_a$ characteristic be

$$\begin{cases} i_a = g_0\left(\dfrac{1}{2a}e_g^2 + e_g + \dfrac{a}{2}\right), \text{ for } e_g \geq -a \\ i_a = 0, \text{ for } e_g \leq -a, \end{cases}$$

giving
$$\begin{cases} g_m = \dfrac{\partial i_a}{\partial e_g} = g_0\left(\dfrac{e_g}{a} + 1\right), \text{ for } e_g \geq -a \\ g_m = 0, \text{ for } e_g \leq -a \end{cases}$$

Let $e_g = -b(1 - \cos\theta)$; so that $g_0$ is the maximum value attained by $g_m$.

Then, according to equation (9),

$$g_t = \frac{1}{2\pi}\int_0^{2\pi} g_m \cos\theta d\theta$$

$$= \frac{1}{\pi}\int_0^{\phi} \cos\theta \cdot g_0\left[1 - \frac{b}{a}(1 - \cos\theta)\right]d\theta$$

$$= \frac{g_0}{2\pi}\cdot\frac{\phi - \sin\phi\cos\phi}{1 - \cos\phi}$$

where $\cos\phi = 1 - (a/b)$

$e_g$ is here regarded as being measured from the point of commencement of grid current, and $g_0$ is the mutual conductance at this point. $g_t$ as a function of $b$ is plotted in Fig. 13, and it can be shown that the former has a maximum value of $0{\cdot}268g_0$ when $b/a = 0{\cdot}650$.

### CONVERSION CONDUCTANCE FOR LINEAR CHARACTERISTIC (CATHODE INJECTION).

Let the $e_g$, $i_a$ characteristic be

$$\begin{cases} i_a = g_0(e_g + a), \text{ for } e_g \geq -a \\ i_a = 0, \text{ for } e_g \leq -a, \end{cases}$$

giving
$$\begin{cases} g_m = \partial i_a/\partial e_g = g_0, \text{ for } e_g > -a \\ g_m = 0, \text{ for } e_g < -a. \end{cases}$$

Let $e_g = -b(1 - \cos\theta)$ giving, as before, $g_0$ as the maximum value of $g_m$.

Then

$$g_t = \frac{1}{\pi}\int_0^{\phi} g_0 \cos\theta d\theta \quad . \quad . \quad . \quad . \quad (11)$$

$$= \frac{g_0}{\pi}\sin\phi$$

where $\cos\phi = 1 - (a/b)$.

$g_t$ as a function of $b$ is plotted in Fig. 13.

The conversion conductance has a maximum value of $g_0/\pi$, occurring when $b = a$.

For any given maximum mutual conductance, it follows from the form of equations (9) and (11) that this (linear) type of characteristic operated at its optimum point gives the largest possible value of conversion conductance. Hence the theorem: The maximum possible value of conversion conductance obtainable from a valve operating with grid or cathode injection is $1/\pi$ of the maximum useful mutual conductance.

## ADDENDUM TO THE PAPER.

(*Received* 1*st August*, 1934.)

Since the submission of the paper, the author has been faced with the necessity of measuring accurately the low values of conversion conductance occurring near the minimum-sensitivity point of frequency-changer valves embodying a "variable-mu" feature. This has led to a modification of the "fundamental output" method (*b*) which is susceptible of the greatest accuracy.

In this new method, the filter circuits of method (*b*) are replaced by a dynamometer instrument. The "oscillator" input is derived from the 50-cycle mains. One of the dynamometer coils is traversed by the anode current of the detector valve under test, while the other coil is supplied with a 50-cycle supply derived from the mains through a suitable phase-shifting device. In this way the 50-cycle component of the anode current may be measured directly.

The dynamometer employed was a Cambridge unipivot wattmeter. The potential coil of 1 000 Ω was connected in the anode circuit and the current coil supplied with its maximum current of 0·5 A. The sensitivity of this instrument was such that full-scale deflection was obtained with a 50-cycle component of 2·26 mA (peak) in the anode current, and the instrument was readable down to a corresponding value of about 3 μA (peak). The new method is as sensitive as, and rather more accurate than, method (*e*) of Section 7.

The currents traversing the two dynamometer coils must be exactly in phase. This has been arranged by the phase-shifting device previously referred to, and checked by means of a cathode-ray oscillograph.

# DISCUSSION ON

## "CATHODE-RAY OSCILLOGRAPHIC STUDIES OF SURGE PHENOMENA."*

**Dr. J. L. Miller** and **Mr. J. E. L. Robinson** (*communicated*): The paper can be divided essentially into two sections. One part deals with experimental results on the impulse-voltage flash-over of porcelain insulators and the breakdown of various types of air and oil gaps, while the other part describes and comments upon the experimental technique employed to obtain those results by means of spark-gaps and the high-speed oscillograph.

Both sections are equally valuable. That part of the paper dealing with the experimental results is essentially a record of a careful laboratory experiment brought to a successful conclusion. It gives us yet another series of breakdown voltages and impulse ratios for various types of gaps, although in the present case the manner in which the material is presented and the frank way in which the difficulties are discussed cannot but increase the confidence of the reader in the value of the results. Unfortunately, such confidence cannot always be associated with many fairly recent publications; in work of this nature we think it is essential to present all details of the experimental set-up and an estimate of the probable or unaccounted inaccuracies, and the absence of such details makes it almost impossible to assess the value of the results.

That part dealing with the measurement technique, however, is essentially specialized and is not applicable to other types of impulse work. For instance, the authors used the oscillograph merely to monitor the impulse wave-shape, since they could not readily rely on the oscillograph to measure voltage correctly to within ± 1·5 per cent. On the other hand, however, it is necessary in work on solid insulation and apparatus where only a few impulses may be used, or where the presence of power-frequency current precludes the use of spark-gaps such as in certain forms of transformer work, to rely entirely on the oscillograph for voltage measurement; and in such cases the authors' technique is not applicable. In work of this nature it is necessary to calibrate the oscillograph against a sphere spark-gap and not, as the authors appear to imply, calculate the sensitivity from the potentiometer ratio. We calibrate, observing all necessary precautions, by recording the flash-over across the sphere gap of a relatively slowly-rising voltage impulse, it being so arranged that flash-over occurs near the crest of the wave. Several measurements are taken in order to examine the variation. The great trouble, of course, in measuring voltage with the oscillograph is that such measurements are always needed in those cases where the presence of power current, or the inability to employ many impulses to set the apparatus by trial, makes it difficult to observe every requirement necessary to obtain the most accurate results.

The requirements to which we refer include means of ensuring that the impulse generator sparks over at constant voltage during calibration, that really accurate means are available for measuring the cathode voltage, that an exceedingly fine trace is maintained on the photographic plate, that the deflection sensitivity is such that a deflection on the screen of the order of several centimetres is possible, and that the wave is quite free from high-frequency superimposed oscillations. By rigorously controlling these factors it is possible to measure voltage with an error certainly not exceeding ± 1 per cent, although, admittedly, errors of ± 2·5 per cent are only to be expected when carrying out rapid and routine work. It will be seen, therefore, that in general we agree with the figure of ± 1·5 per cent given in the paper, and, indeed, we are very glad to see for, we think, the first time in print, a frank statement of the order of accuracy expected in such measurements.

It is to be noted that the authors used 1/5, 1/50, and 1/580 waves. It is always difficult to decide on the waves to be used in an investigation of the present nature, and there is a great deal to be said for the authors' choice. We should be interested to hear, however, the reasons for their choice of the last-mentioned wave, which, for all ordinary purposes, is an infinite rectangular one. Also, what were their reasons for preferring the 1/50 wave to a 1½/40 wave? The latter, of course, is now generally recognized as standard in the United States.

In this connection it would appear strange that since laboratory impulse-voltages should simulate all the conditions appertaining to lightning on transmission lines, no laboratory (including the authors') has yet sponsored the use of voltages simulating one of the most dangerous aspects of lightning, that is, voltages having very rapid rates of rise or fall. This applies, of course, particularly to the impulse testing of transformers which may have to withstand, under direct lightning-stroke conditions, very rapid rates of voltage-rise—the actual rate of rise under these conditions has not yet been established—and certainly have to withstand the interturn stresses due to the rapid collapse of voltage when an insulator flashes over.

We have held for some time the opinion that such tests are necessary, and we have recently made experiments on the behaviour of transformers under such conditions. Rapid rates of controlled impulse voltage-rise on transformers are difficult to obtain, since the necessary series damping-resistance (often greater than that required for insulator testing), combined with the effective earth capacitance of the transformer, has a relatively great time-constant. Accordingly, in this country if manufacturers ever carry out impulse acceptance-tests, there is a lot to be said for the use of an additional standard wave having as steep a front as possible and a chopped back (obtained by allowing an insulator to flash over), and therefore it would have been of considerable interest if the authors had given us some figures relating to very rapid rates of voltage-change.

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* Paper by Dr. T. E. Allibone, Mr. W. G. Hawley, and Mr. F. R. Perry, (see vol. 75, page 670).

They define their wave fronts as the time necessary to reach maximum value, but we should value their opinion of the several alternative methods. One method, for instance, defines the front as the time taken for the voltage to rise from 10 per cent to 90 per cent of the maximum, multiplied by 1·25. Frequently, when comparing waves, we count the front as the time taken for the voltage to rise from zero to 90 per cent of the maximum value. The reason for this is that the crest is usually very rounded; in fact, under many circumstances it is possible to have two waves having equal times to the maximum value, but quite widely differing maximum voltage gradients. We agree, however, that for the work described in the paper, where the front is essentially controlled by one exponential function, the authors' definition is quite admissible, and any scheme whereby counting only begins after the voltage has reached 10 per cent of maximum would only be an excuse for ignoring initial oscillations or fog due to a bad technique.

We note with great interest that the authors no longer use a solid-dielectric delay cable, but now employ an air-insulated one. The oscillogram in Fig. 1 shows the distortion that occurs, and, as we have pointed out in our previous publications, we have always so arranged matters that for much of our work no delay cable is used at all. It is a point of considerable importance when measuring the faster fronts, and we are glad to have practical confirmation from another laboratory of our own views. We are not suggesting, of course, that the use of a solid cable is improper for many classes of work, but its use is preferably to be avoided in the laboratory.

The authors refer to the need for the suppression of oscillations superimposed on the applied impulse wave. Everyone, of course, will agree with this statement, although circumstances certainly arise when the prevention of oscillation presents difficulties. In general, for simple test objects, the higher-frequency oscillations, which usually occur low down on the front of the wave, are the more difficult to suppress, although for breakdown tests on the tail of the waves they do not cause any error if their amplitudes are small. In the paper, for instance, a few oscillograms show slight ordinate oscillations on the fronts, and one or two show oscillations in the abscissa direction. While all these have no effect whatever on the present results (we are surprised, however, that abscissa oscillations are present with such relatively slow rates of voltage-rise), if one is interested in the fronts of waves, as we are, so that time-sweeps having durations as short as 1 or 2 microseconds are employed, then even such oscillations as these should be reduced very considerably. With some of the waves we have used, such as a 300-kV 0·2/0·2 wave, this presents considerable difficulty, since the durations of the time-sweeps used (at any rate the initial part showing the front) are of the order of the duration of the tripping impulse or of the interference due to electromagnetic coupling at spark-over. These are points to which we have given a good deal of attention, and we agree wholeheartedly with the authors' criticism of the possible inaccuracies in the time from zero to crest voltage given in numerous published oscillograms, particularly in those where long time-bases are employed and the auxiliary circuits used give rise to a considerable amount of fogging at the beginning. We have endeavoured always to maintain a recording technique such that the fronts could be accurately and clearly delineated on short time-bases. Oscillations are rarely seen, of course, on fronts of waves, simply because they are usually drawn on relatively long time-bases.

We are interested in the criticism of the American co-ordinating gap. Since this is a point of some importance, it is a pity that the authors did not give us a few figures relating to this gap. Its behaviour, compared with that of a suspension insulator, when flashing over on the fronts of steep waves would be of considerable interest. The effect of moisture on the flash-over voltage of an insulator with arcing fittings is consistent with our findings. We have never obtained any wet flash-over voltages without these fittings, but we are surprised at the relatively low wet flash-over voltages found under these conditions.

The distortion of wave-shape owing to corona current just prior to the breakdown of certain types of air gap is interesting, and we can confirm this phenomenon. We have also noted the clear-cut transition of the oscillograph trace at the instant of breakdown of an oil dielectric, or of a sphere-sphere air gap.

**Dr. T. E. Allibone** and **Messrs. W. G. Hawley** and **F. R. Perry** (*in reply*): We wish to thank Dr. Miller and Mr. Robinson for their very valuable communication. We note their remarks concerning the measuring technique described in the paper. It is not suggested that the method outlined is suitable for all types of impulse testing, but it is doubtful whether any one method could satisfy all the various testing conditions except that of using the cathode-ray oscillograph calibrated by an absolute method. We feel that this should be the final goal, but it is admitted that this aim presents a large number of difficulties. The method suggested by Dr. Miller and Mr. Robinson is open to criticism on the grounds that, as the calibration of the oscillograph against the sphere gap is made with a slow-fronted wave, the results obtained may not necessarily be correct for waves having a steeper front, unless the potential divider is above suspicion. It is well known that a resistance potential-divider has to be carefully designed in order to avoid the errors due to stray earth capacitance, and a capacitance potential-divider is liable to introduce high-frequency oscillations into the impulse circuit. These limitations, therefore, are a serious factor, even though the cathode-ray oscillograph is calibrated against a sphere gap, in the manner described, and if these errors can be satisfactorily eliminated the use of the oscillograph as an absolute method of measurement is brought nearer. Moreover, it is desirable that eventually the oscillograph should be used to calibrate the sphere gap for impulse voltages, rather than vice versa, for, as we have pointed out, the accepted normal-frequency calibration of the sphere gap can certainly not be used, without due caution, for impulse work.

With reference to the wave shapes used in the investigation, it should be pointed out that, at the time the work was in progress, there was certainly no standard wave among the various American and European laboratories. The 1/5 and 1/50 waves were chosen as representative wave-shapes likely to become accepted as convenient standards for impulse testing. The 1/580 wave was chosen as a practical realization of a rectangular wave; it is useful in assessing the effect of length of wave tail on spark-over, and if applied to transformers gives an approximation to the maximum stresses across major insulation therein. The question of choice of wave-shape is at present under consideration by the International Electrotechnical Commission.

Dr. Miller and Mr. Robinson raise the question of waves having a steep front and a steep tail. Waves of this type occur when line insulators or co-ordinating gaps are subjected to maximum spark-over conditions, but this is outside the scope of the present investigation, which was confined to minimum spark-over measurements only. We are of the opinion that it is desirable that any apparatus connected to a transmission line should be capable of withstanding the abnormal stresses resulting from either minimum or maximum spark-over voltages of the line insulation.

The stresses resulting from these two extreme conditions in a transformer are of a quite different character and, hence, the satisfactory behaviour of the transformer under one test may not guarantee an equally good result under the other test. The relative severity of the two tests depends a good deal on the characteristics of the test object, and they cannot therefore be argued from first principles.

With regard to the definition of the wave front, we desired in the paper to draw attention to the several methods still used for this purpose and to the desirability of obtaining agreement between the various laboratories. Although it is suspected that certain definitions have in the past been adopted to suit the special conditions caused by a deficient technique, in general it can be said that quite good arguments can be advanced for most of the various methods used. At the same time it is doubtful whether any one method shows marked superiority over the others, and the chief necessity at the moment is to decide on an agreed definition of a simple nature. It is not yet clear, however, whether one definition will be adequate for both maximum and minimum spark-over conditions. This matter of definition of wave front is under consideration by the I.E.C. and national committees, and it is expected that agreement as to choice of wave definition will be reached in the near future.

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# INSTITUTION NOTES.

### Faraday Medal.

At the Ordinary Meeting of the Institution held on the 24th January, 1935, the President announced that the Council had that day made the thirteenth award of the Faraday Medal to Dr. F. B. Jewett (New York).

### Honorary Member.

At the same meeting the President also announced that the Council had elected Lord Hirst of Witton to be an Honorary Member of the Institution.

### Coopers Hill War Memorial Prize and Medal.

The triennial award of the above Prize and Medal, which fell in 1934 to the Institution, has been made by the Council to Mr. Alexander M. Wright, M.Sc., Associate Member, for his paper entitled "Electrification of Railways."

### List of Members.

Copies of the List of Members corrected to the 1st September, 1933, are still available. Any member wishing to receive a copy should apply to the Secretary.

### Discussions at Meetings.

The Council desire to remind the members that verbal contributions to the discussions at meetings should not be read from manuscript, the view being held that the presentation of remarks in this manner is contrary to the true spirit of a "discussion," and that contributions in manuscript should, more appropriately, be sent to the Secretary for publication in the *Journal* as "communicated remarks."

### Wireless Section Informal Meetings.

The Wireless Section Committee have decided, with the approval of the Council, to include in the programme of activities of the Section informal discussions of a popular character on subjects of wide interest, such as broadcasting, transmitters, and receivers.

The meetings, which will be held at 6 p.m. (light refreshments at 5.30 p.m.), will be open to non-members, and members of the Institution are invited to introduce non-members to the meetings. Tickets of admission will not be required. The following is the programme of these informal meetings for the present Session:—

29th January, 1935: Discussion on "The Cause and Prevention of Valve Failures in Broadcast Receivers" (opened by Mr. T. E. Goldup).

26th February, 1935: Discussion on "Production Testing of Broadcast Receivers" [opened by Mr. F. Murphy, B.Sc.(Eng.)].

26th March, 1935: Discussion on "The Servicing of Broadcast Receivers" (opened by Mr. A. Hall).

## Graduateship Examination Results: November, 1934.

*Passed.**

Amos, K. J. (Bromley, Kent).
Bate, R. (Chingford).
Bedford, G. F. (London).
Bradley, J. F. (Hawick).
Bradley, J. H. (Rawdon).
Calvert, R. (Bingley).
Carrette, A. D. (Leeds).
Clark, W. B. (Twickenham).
Dick, R. G. (Glasgow).
Dixon, I. B. (Hockley, Essex).
Dolan, W. H. (Cricklewood).
Donnelly, P. J. (Seaview, Isle of Wight).
Dossor, F. (Hull).
Dunkel, C. P. (Oxford).
Finucane, P. C. (Loughborough).
Fowlie, W. S. (Ilford).
Goodall, W. E. (Nuneaton).
Gray, W. (Sunderland).
Greenlees, A. E. (Kenton, Middlesex).
Guthrie, A. (Dumfries).
Hanna, M. (Belfast).
Hawker-Smith, R. E. (Walton-on-Thames).
Hayward, J. R. G. (London).
Hendry, N. (Newcastle-upon-Tyne).
Hodges, L. W. (Pontypridd).
Holt, P. (London).
Howard, F. W. M. (London).
Irvine, F. J. (Barrow-in-Furness).
Jamison, A. (Bangor, Co. Down).
Jones, R. H. (Birkenhead).
Lowde, E. A. (London).
Lowe, B. (Ashton-under-Lyne).
Macaulay, A. J. (Loughborough).
Marr, R. (Sheffield).
Mehta, H. R. (London).
Miller, A. A. (Glasgow).
Neave, D. P. B. (London).
Neave, J. W. C. (Hindhead).
Needham, A. W. (Burnage).
Neill, V. A. (Hayes, Middlesex).
New, C. M. (Bridgwater).
Parker, G. (Chorley).
Parker, W. F. (Port Sunlight).
Pearson, L. A. (London).
Philps, G. A. (Margate).
Possnett, A. F. J. (Welling).
Rigby, N. H. (Bolton).
Styles, G. E. (London).
Tantawi, M. K. M. (London).
Thomas, E. C. (Portswood).
Tucker, J. H. L. (Wallsend).
Vallis, F. (Nuneaton).
Walker, A. (Cambridge).
Williams, J. C. (Cardiff).
Winskill, J. E. (Middlesbrough).
Yells, M. H. (London).
Yoh, J. (Chelmsford).

*Passed PART I only.*

Bennett, F. I. (Cardiff).
Blomfield, F. W. R. (Norwich).
Buckle, G. W. V. (Manchester).
Bullen, H. H. (Swansea).
Ellis, R. (Rugby).
Elphick, J. F. (Winchester).
Evans, A. C. (Blaenavon).
Gallon, C. (Redcar).
Gibson, T. T. (Worsley).
Harris, J. B. (London).
Hatt, G. W. (London).
Kinvig, T. F. (Douglas, I.O.M.).
Lomax, G. R. (Castle Douglas).
Lumsdaine, W. N. (Edinburgh).
McKie, N. A. M. (Annan).
Maurice, R. B. (High Wycombe).
Meredith, D. L. (Cheltenham).
Richardson, G. (London).
Rowland, F. G. (Sleighford).
Sherlock, H. W. (Loughborough).
Smith, A. (Aberavon).
Spencer, T. (Aberavon).
Wakefield, J. A. P. (Newcastle-upon-Tyne).
Wharry, R. (Loughborough).
Wright, H. J. (Ipswich).

*Passed PART II only.*

Batty, K. T. (Barrow-in-Furness).
Evans, T. F. (Cardiff).

---

* This list also includes candidates who are exempt from, or who have previously passed, a part of the Examination and have now passed in the remaining subjects.

## National Certificates and Diplomas in Electrical Engineering.

The results of the examinations in connection with the above are as follows for the year 1934:—

*England and Wales.*

| | *Pass* | *Fail* |
|---|---|---|
| Ordinary Certificate .. .. | 804 | 575 |
| Higher Certificate .. .. | 353 | 238 |
| Higher Certificate endorsed .. | 45 | 16 |
| Ordinary Diploma .. .. | 18 | 11 |
| Higher Diploma .. .. | 9 | 4 |
| | 1 229 | 844 |

*Scotland.*

| | *Pass* | *Fail* |
|---|---|---|
| Ordinary Certificate .. .. | 19 | 7 |
| Higher Certificate .. .. | 16 | 4 |
| Higher Diploma .. .. | 14 | 8 |
| | 49 | 19 |

## Informal Meetings.

### 171st Informal Meeting (29th October, 1934).

*Chairman*: Professor W. M. Thornton, O.B.E., D.Sc., D.Eng. (President).

*Subject of Discussion*: " First Principles " (introduced by the President).

*Speakers*: Messrs. A. Morgan, E. Kilburn Scott, W. E. Warrilow, F. Jervis Smith, J. F. Shipley, Lieut.-Col. C. J. Aston, R.S., Messrs. P. Higgs, G. Waters, G. J. Maughfling, R. H. Woodall, and E. F. Clark.

### 172nd Informal Meeting (12th November, 1934).

*Chairman*: Mr. P. P. Wheelwright.

*Subject of Discussion*: " The Efficient Use of Distribution Capital " (introduced by Mr. J. M. Kennedy).

*Speakers*: Messrs. H. J. Cash, J. H. Sumner, B.Sc.Tech., A. N. D. Kerr, E. Kilburn Scott, H. Brierley, P. P. Wheelwright, R. O. Kapp, B.Sc., F. W. Shilstone, J. L. Egginton, T. G. Procter, P. F. Grove, M.A., and J. W. Perkins.

### 173rd Informal Meeting (26th November, 1934).

*Chairman*: Mr. A. N. D. Kerr.

*Subject of Discussion*: " Modern Electric Vehicles " (introduced by Lieut.-Col. G. D. Ozanne, M.C.).

*Speakers*: Messrs. W. E. Warrilow, A. F. Harmer, L. Murphy, G. H. Fletcher, P. Jackson, A. C. Morrison, T. W. Read, G. F. Bedford, A. Morgan, P. P. Wheelwright, W. A. Edwards, C. F. Roberts, H. Brierley, A. J. Bousfield, A. G. Kilby, E. S. Waddington, H. G. Wilson, T. C. Elliott, and S. H. Chase.

### 174th Informal Meeting (10th December, 1934).

*Chairman*: Mr. F. C. Raphael.

*Subject of Discussion*: “Ideal Service from the Consumer's Point of View” (introduced by Mr. P. P. Wheelwright).

*Speakers*: Messrs. A. N. D. Kerr, P. F. Grove, I. D. Campbell, B.Sc.(Eng.), F. Jackson, Miss J. Whitgift, Messrs. A. Gowans Whyte, A. V. Cross, H. Brierley, V. W. Dale, A. Morgan, F. Jervis Smith, W. A. Ritchie, J. M. Kennedy, E. S. Ritter, A. C. H. Frost, A. H. Olson, B.Sc.(Eng.), H. G. F. Lambe, C. Barber, M. Davidson, F. C. Raphael, and J. R. Bedford.

### 175th Informal Meeting (17th December, 1934).

*Chairman*: Mr. H. Brierley.

*Subject of Discussion*: “Modern Fuse Protection (400 V to 132 kV)” (introduced by Mr. J. F. Shipley).

*Speakers*: Messrs. H. Simmonds, J. W. Gibson, J. D. Mortlock, W. E. Warrilow, A. G. Hilling, E. S. Ritter, A. Morgan, P. Higgs, A. W. Metcalf, R. Leach, and A. J. Bousfield.

## Proceedings of the Meter and Instrument Section.

### 47th Meeting of the Meter and Instrument Section, 2nd November, 1934.

Mr. W. Lawson, Past-Chairman, took the chair at 7 p.m.

The minutes of the meeting held on the 4th May, 1934, were taken as read and were confirmed and signed.

Mr. Lawson announced the Council's award of Premiums (see vol. 74, page 603) for papers read before the Section during the session 1933–34. He then vacated the chair, which was taken by Prof. J. T. MacGregor-Morris, Chairman.

A vote of thanks to Mr. Lawson for his services as Chairman during the session 1933–34, proposed by Mr. O. Howarth and seconded by Mr. H. P. Bramwell, was carried with acclamation.

Prof. MacGregor-Morris then delivered his Inaugural Address.

A vote of thanks to the Chairman for his Address, proposed by Mr. W. Lawson and seconded by Dr. E. H. Rayner, was carried with acclamation.

The meeting terminated at 8.30 p.m.

### 48th Meeting of the Meter and Instrument Section, 7th December, 1934.

Prof. J. T. MacGregor-Morris, Chairman of the Section, took the chair at 7 p.m.

The minutes of the meeting held on the 2nd November, 1934, were taken as read and were confirmed and signed.

A paper by Mr. J. L. Ferns, B.Sc., Graduate, entitled “Some Suggestions on the Equipment and Routine of the Meter Departments of Supply Undertakings,” was read and discussed.

The meeting terminated at 9.32 p.m. with a vote of thanks to the author, which was moved by the Chairman and carried with acclamation.

## Proceedings of the Transmission Section.

### 1st Meeting of the Transmission Section, 21st November, 1934.

Prof. W. M. Thornton, O.B.E., D.Sc., D.Eng., President, took the chair at 6 p.m. and announced the constitution of the Committee for 1934–35 (see page 121). He then vacated the chair, which was taken by Mr. R. Borlase Matthews, Chairman of the Section, who delivered his Inaugural Address (see page 17).

A vote of thanks to the Chairman for his Address, proposed by the President and seconded by Mr. W. E. Highfield, was carried with acclamation.

The meeting terminated at 7.25 p.m.

### 2nd Meeting of the Transmission Section, 19th December, 1934.

Mr. R. Borlase Matthews, Chairman of the Section, took the chair at 6 p.m.

The minutes of the meeting of the 21st November, 1934, were taken as read and were confirmed and signed.

A paper by Mr. O. Howarth, Member, entitled “The Control of Voltage and Power Factor on Interconnected Systems,” was read and discussed.

The meeting terminated at 7.57 p.m. with a vote of thanks to the author, which was moved by the Chairman and carried with acclamation.

## Transfers of Members.

The following transfers have been effected by the Council:—

*Student to Graduate.*

Adamson, Alexander Rae.
Barkham, Ronald Hugh M. B.Sc.(Eng.).
Bomford, Leslie, B.Sc.Tech.
Chakravarti, Sitanshu Shekhar.
Coode, Arthur Michael M.
Cope, Francis Bernard, B.Sc.(Eng.).
Dippy, Robert James, B.Sc.(Eng.).
Easterbrook, Alan Bickle.
Gaymer, John Edward I.
Grieve, Arthur James H.
Howell, Carrington John, B.Sc.(Eng.).
Kassell, Edward Douglas, B.Sc.
Keene, Thomas Roger.
Kennedy, William Dennis, B.Sc.Tech.
Pearce, Leslie John.
Peiris, Seymour Wilfred, B.Sc.(Eng.).
Raven, Arthur, B.Sc.
Rhodes, James, B.Sc.(Eng.).
Rolfe, Norman Charles, B.Sc.(Eng.).
Rothwell, Carl.
Rusk, Archibald, B.Sc.
Starkey, Denis William F.

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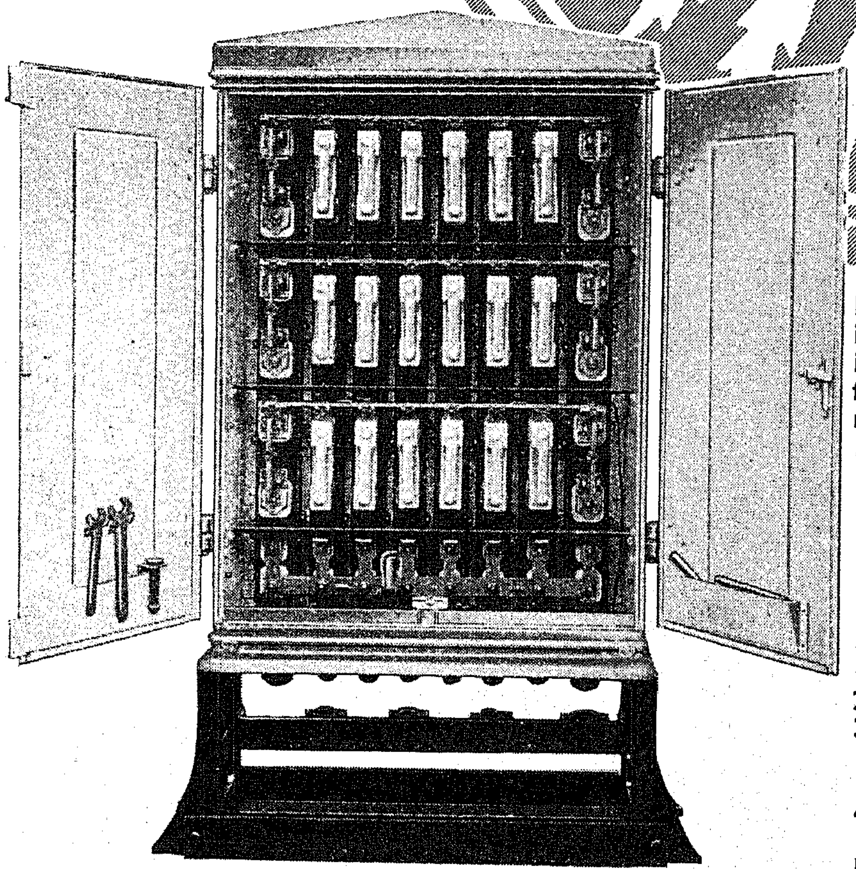

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3. Handles fitted with self-aligning contacts for wire or Zenal fuses, or arranged for English Electric high rupturing capacity enclosed fuses.
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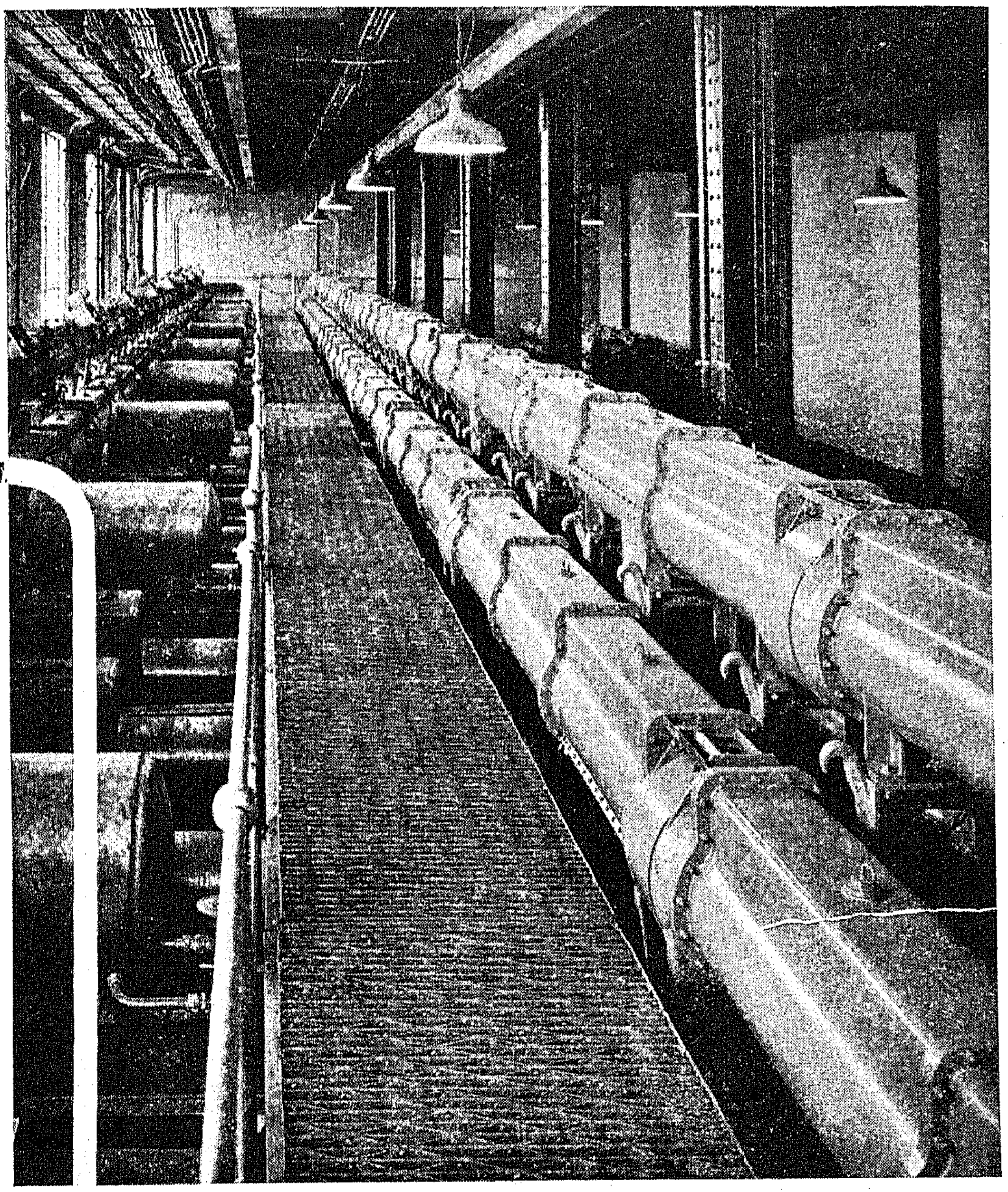

BUSBAR CHAMBERS

**Aluminium alloy**

THIS illustration of aluminium busbar chambers shows a view along the cat-walk of the 11,000 volt, metal-clad switchboard installed at Blackburn Meadows power station, Sheffield (supplied by the General Electric Co. Ltd. of England). The breaking capacity of the circuit breakers is 1,500,000 kVA. Since aluminium is non-magnetic, it comes within the group of metals available for busbar chambers. It is chosen in preference to other metals on account of its cheapness, ease in casting and good machining properties. For applications of this nature, the lightness of aluminium is of real value in reducing erection costs.

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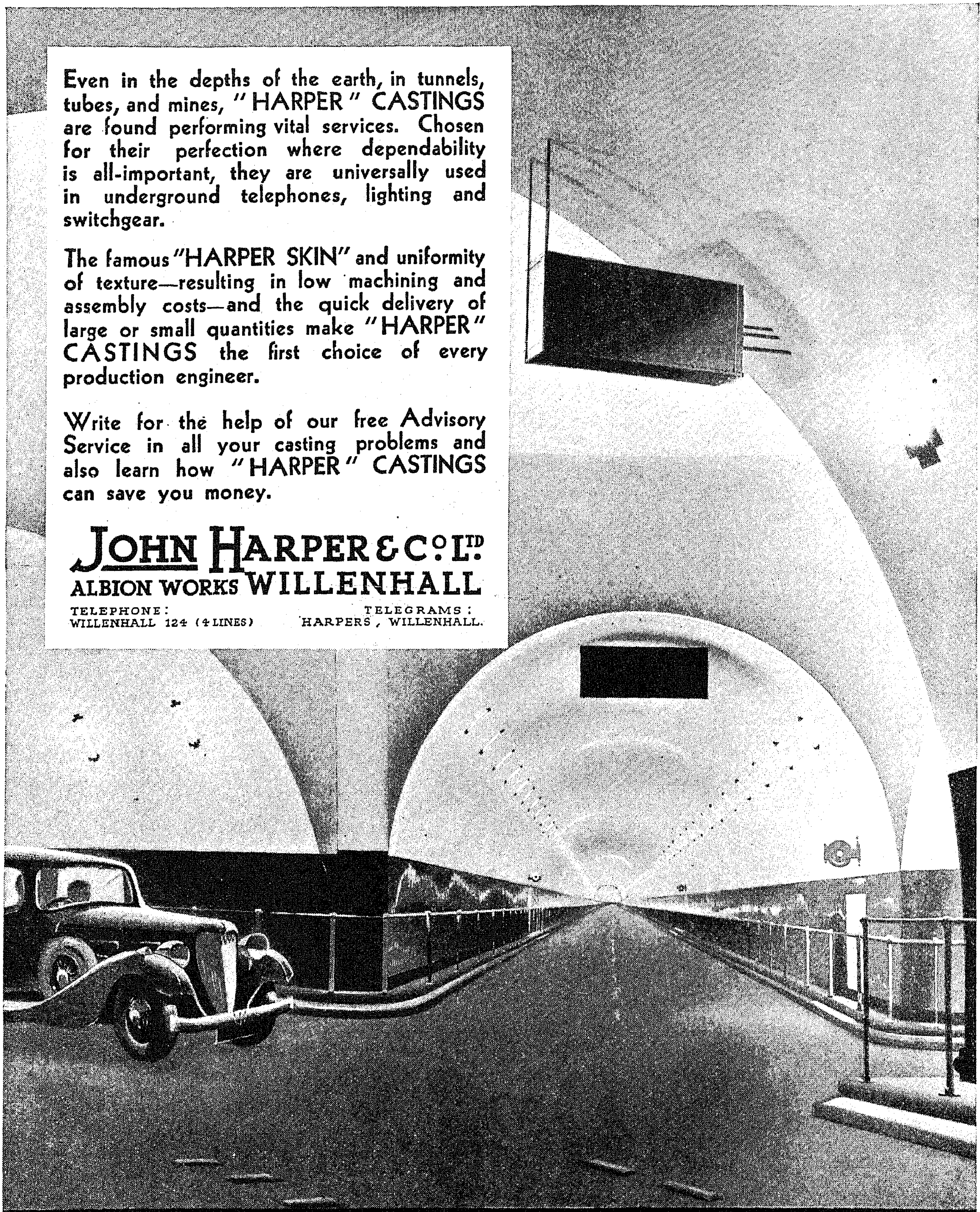

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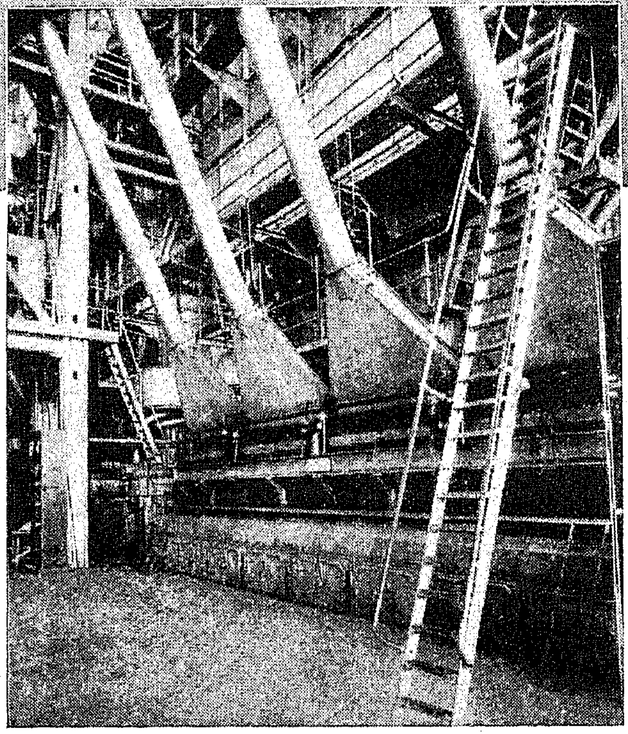

By courtesy of South African Railways and Harbours

**IN 1931,** four B. & W. Boilers were ordered, each for a normal evaporation of 160,000 lbs. of steam per hour at 752° F. with a safety valve load of 258 lbs. per sq. in. These boilers are fitted with B. & W. forged steel return bend economisers, B. & W. plate type air heaters, and are fired with B. & W. Style 28 Stokers 32′ 0″ wide x 20′ 0″ long in Bailey Furnaces. The contract included the boiler-house building and all accessories. An additional boiler duplicating the above was ordered in 1934.

THE BOILER ILLUSTRATED IS ONE OF THE ABOVE

| | |
|---|---|
| TOTAL TIME OF STEAMING .. | 12,918 hours. |
| COAL BURNED .. .. .. | 180,852 tons. |
| FURNACE MAINTENANCE .. .. | NIL |
| STOKER MAINTENANCE .. .. | NIL |

These stokers are the widest B. & W. travelling grate stokers **in operation,** but are exceeded in size by eight stokers ordered in 1934—each being 33′ 0″ wide x 20′ 0″ long—for the Klip Generating Station, owned by The Electricity Supply Commission of the Union of South Africa and operated by the Victoria Falls & Transvaal Power Co., Ltd., who now operate or have on order a total of 140 B. & W. Boilers and 20 Bailey Furnaces.

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One unique advantage of the Ferranti Prepayment Meter is the complete separation of the coin barrel from the meter itself. The collector can in no way interfere with the metering mechanism. On the other hand, the electrician cannot remove the coin barrel when effecting price changes in the meter—price changes being made by a simple conversion on site, the removal of one gear-set and the replacement of another.

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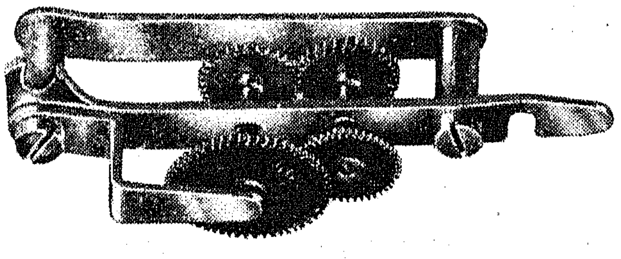

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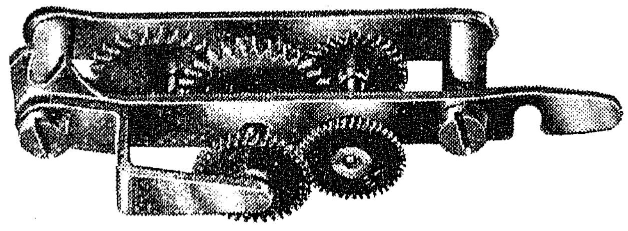
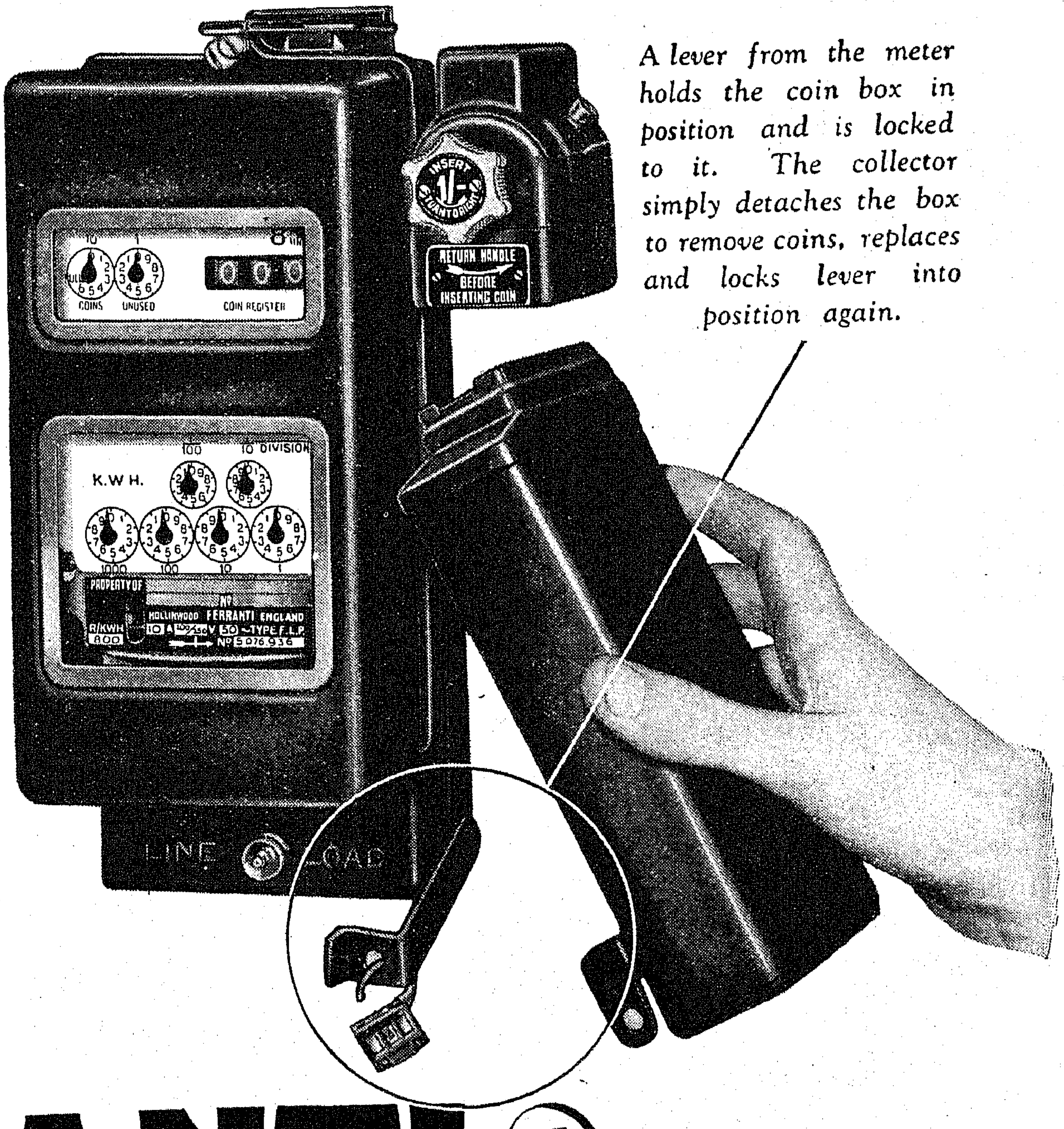
Gear changes are stocked for every conversion—from ½d. per unit to 3/- per unit. Two screws release the gear set, so that the actual change is a matter of a few seconds.



**SHILLING GEARING**
Gear changes cover complete range from ½d. to 3/- per unit.



*A lever from the meter holds the coin box in position and is locked to it. The collector simply detaches the box to remove coins, replaces and locks lever into position again.*

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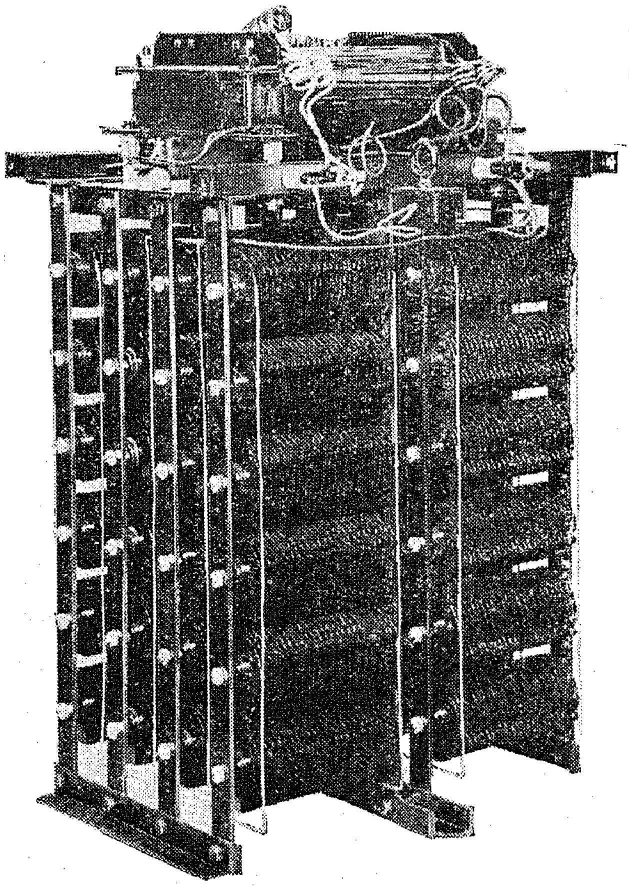

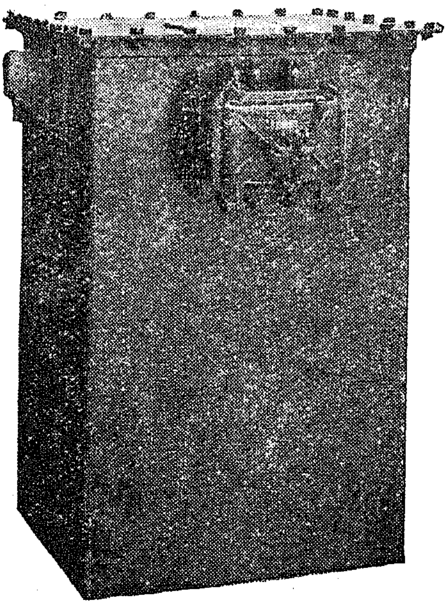

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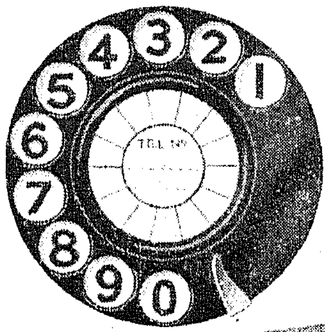

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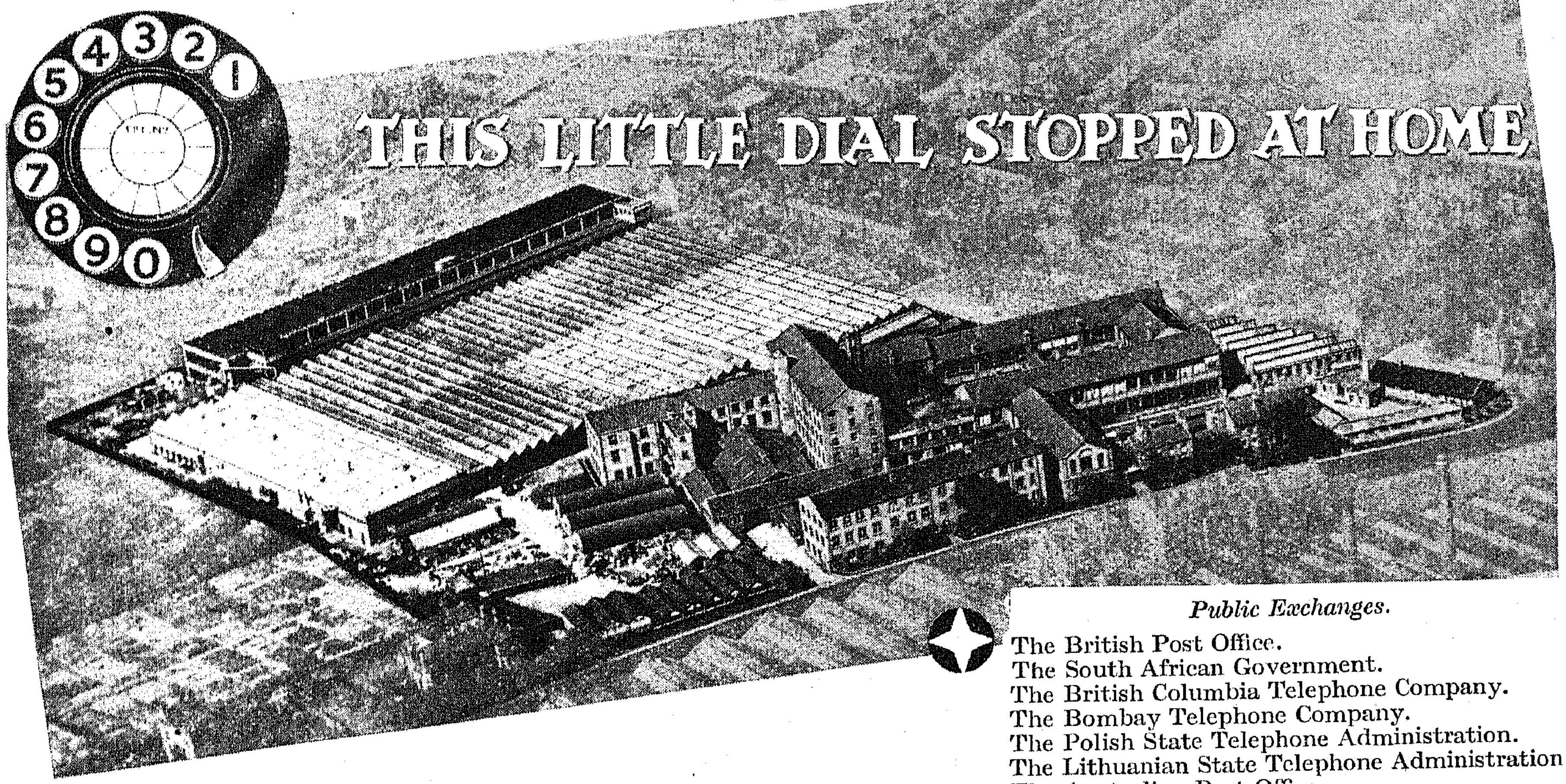

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The Bombay Telephone Company.
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The Lithuanian State Telephone Administration.
The Australian Post Office.
Anglo-Portuguese Telephone Co.
Jamaica Telephone Co.
Hull Corporation Telephone Dept.
Venezuela Telephone & Electric Appliance Co., Ltd.
Etc., Etc.

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Spillers Ltd., Bristol and Cardiff.
Steel-, Peech & Tozer, Ltd., Sheffield.
Cremola Food Products, Ltd., Glasgow.
Coronet Camera Co., Birmingham.
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W. & R. Jacobs, Ltd., Liverpool.
Callard & Bowser, Ltd., London.
Fuller Accumulator Co. (1926) Ltd., Essex.
Threlfalls Brewery Ltd., Salford.
Columbia Graphophone Co. Ltd., London.
J. A. Hunter & Co., Liverpool.
Imperial and International Communication, Ltd., London.
Odhams Press Ltd., Manchester.
L. C. Smith & Corona Typewriter Co., Ltd., London.
Great Universal Stores Ltd., Manchester.
Kye Lamp Works, London.
J. S. Fry & Sons, Ltd., Bristol.
Singer Manufacturing Co., Ltd., Glasgow.
London, Midland and Scottish Railway Co., Euston.
Brooks Motors Ltd., Huddersfield.
Hugon & Co., Ltd., Manchester.
Dorman, Long & Co., Middlesbrough.
C.W.S. Soap Works, Irlam.
Canadian Pacific (S.S. " Empress of Britain ").
Salt Union Ltd., Winsford.
Comper Aircraft Co., Hounslow.
North British Rayon Ltd., Jedburgh.
Sandeman's Varnish Ltd., Glasgow.
Ransomes and Rapier Ltd., Ipswich.
Calico Printers Association, Dinting.
A. C. Sphinx Sparking Plug Co., Ltd., Birmingham.
Etc., Etc.

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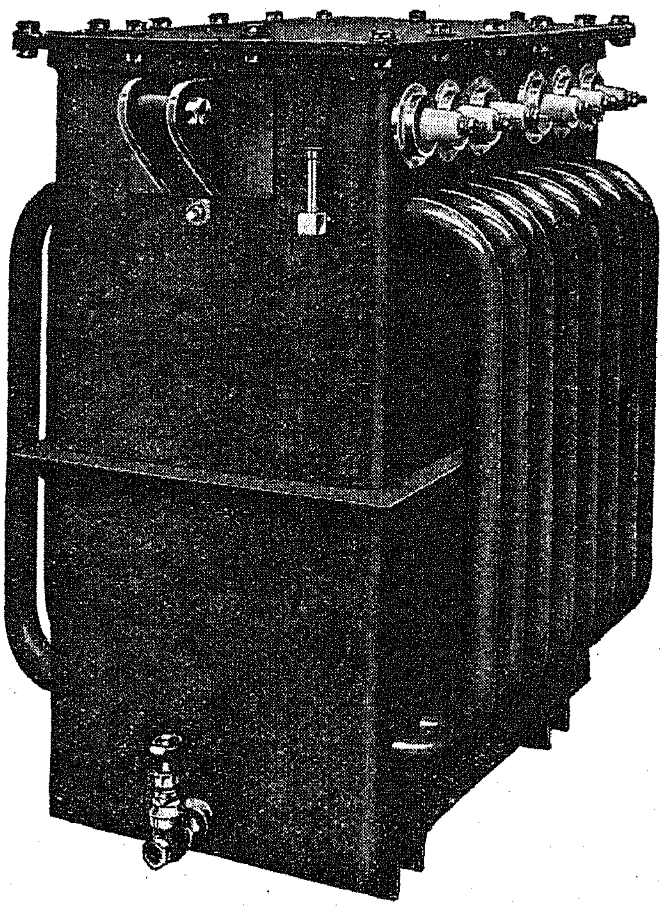

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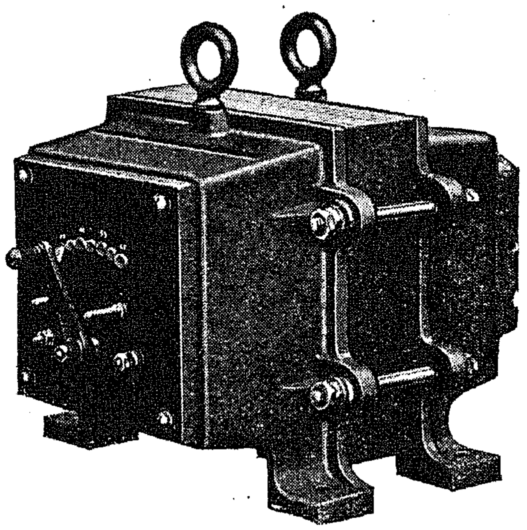

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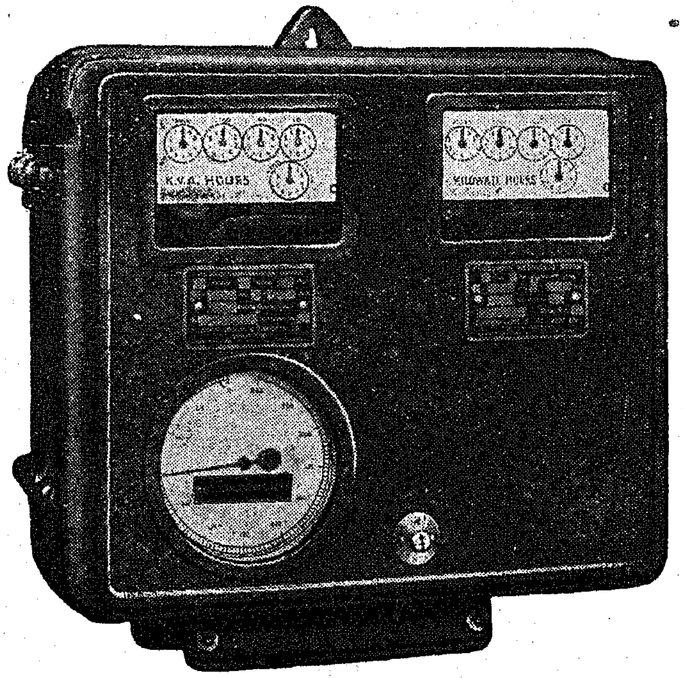

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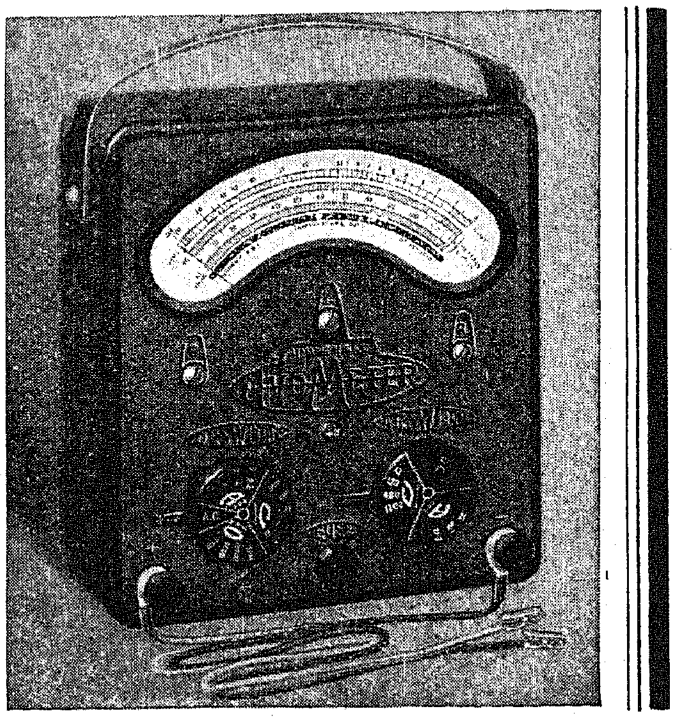

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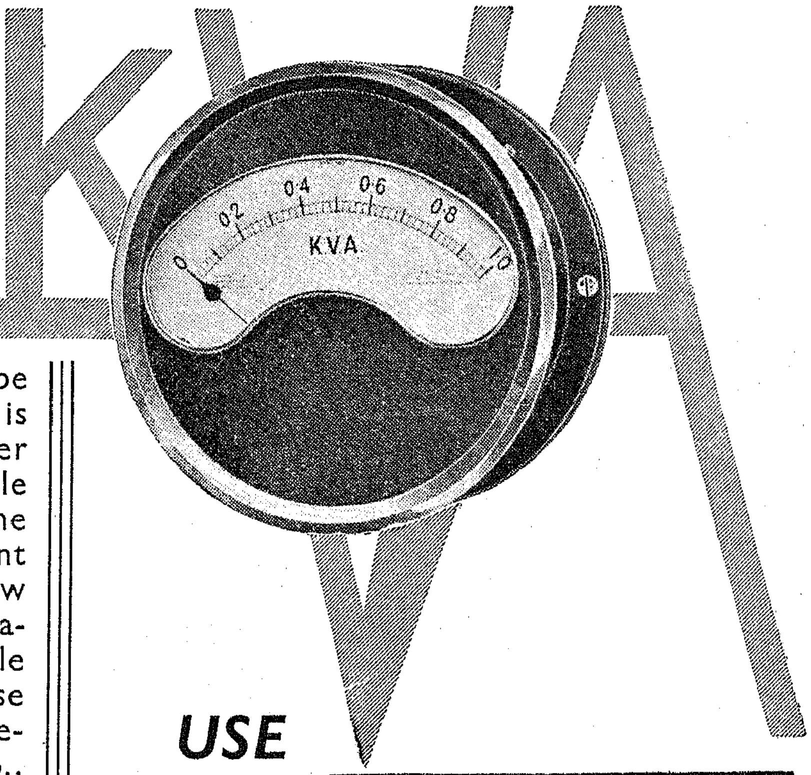

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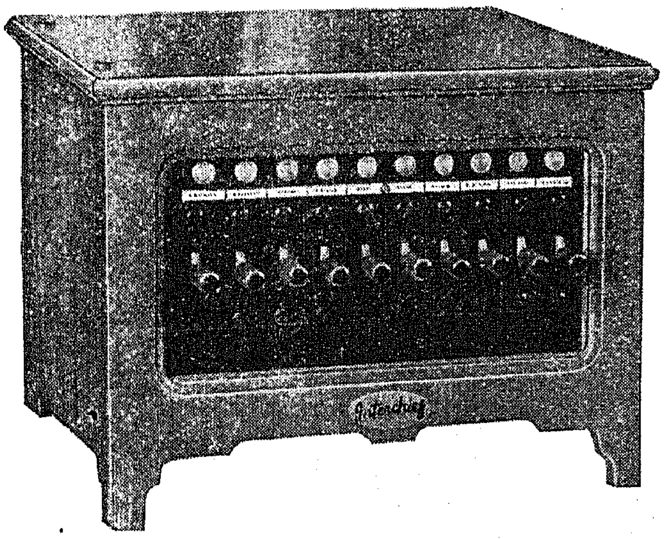

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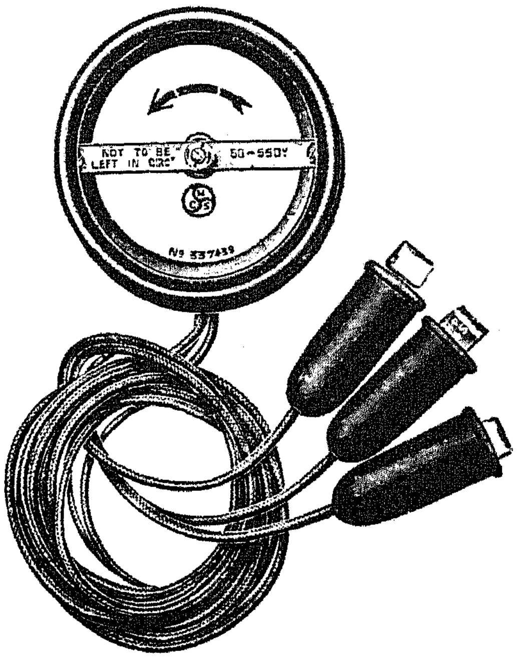

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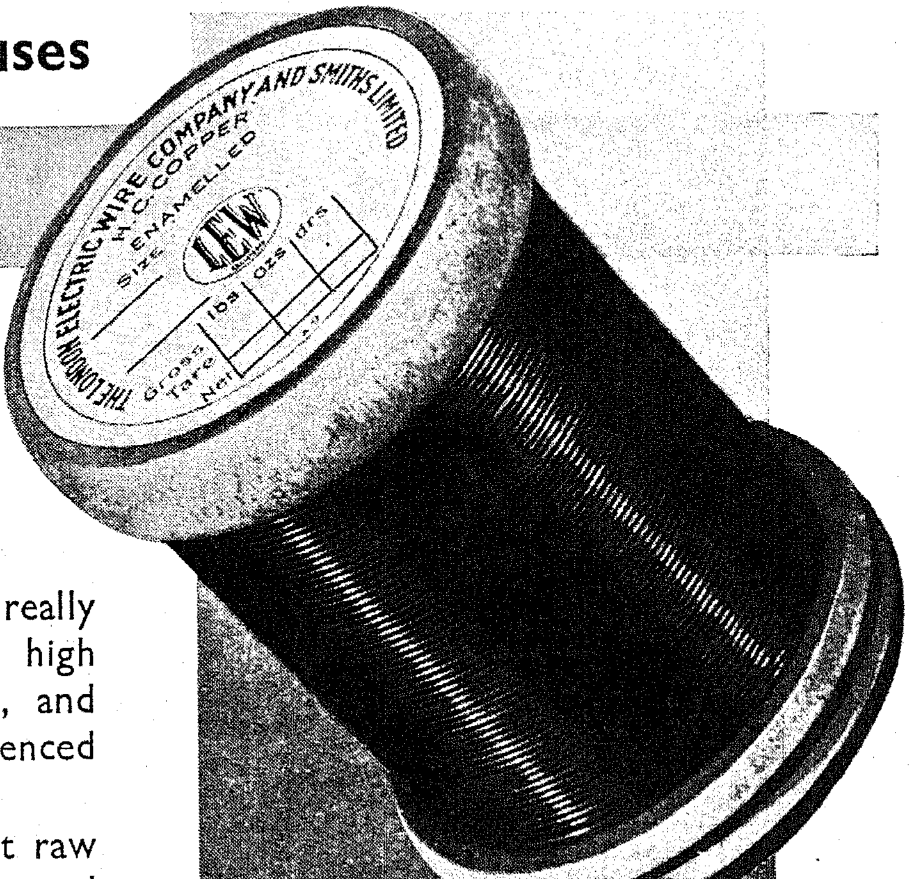

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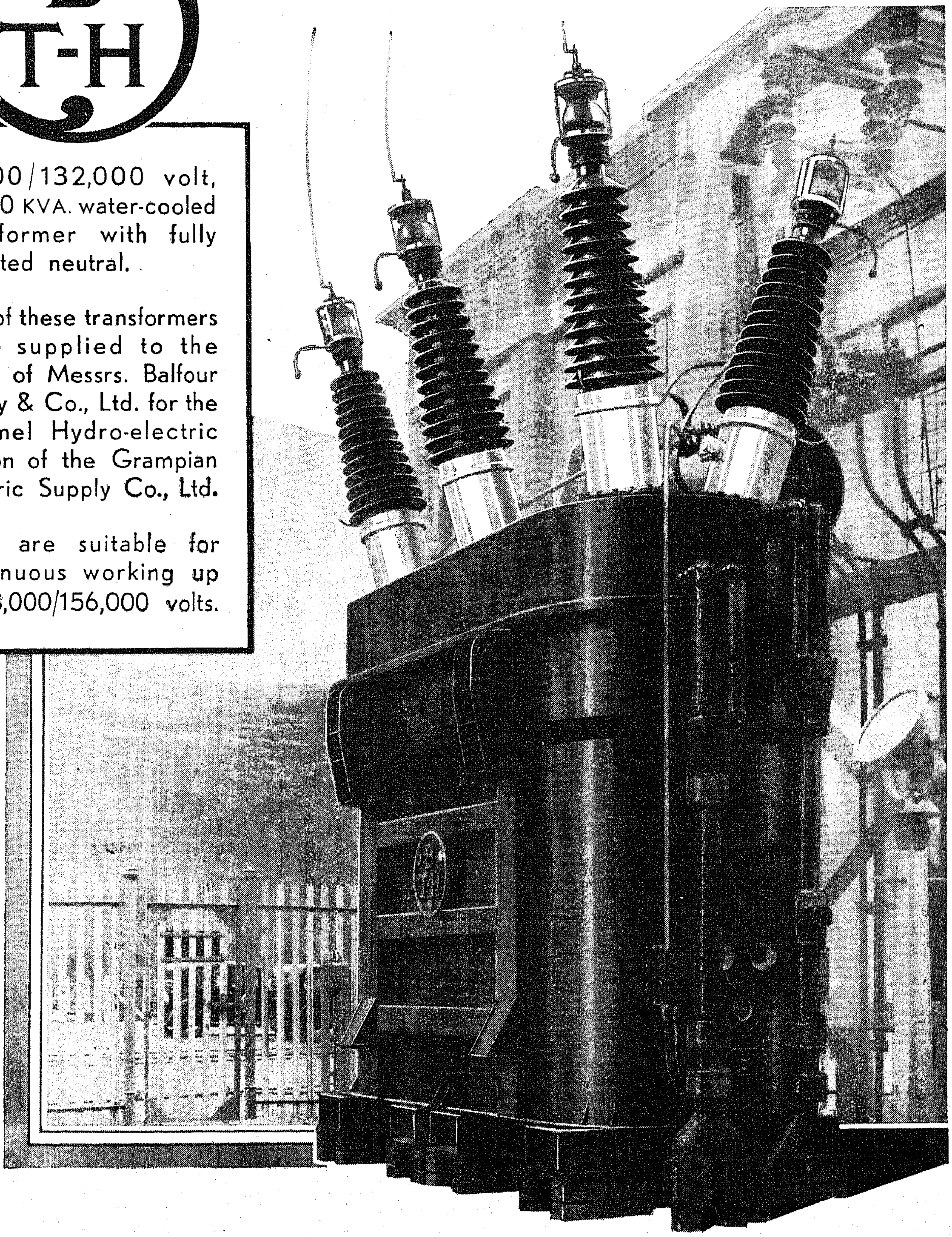

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